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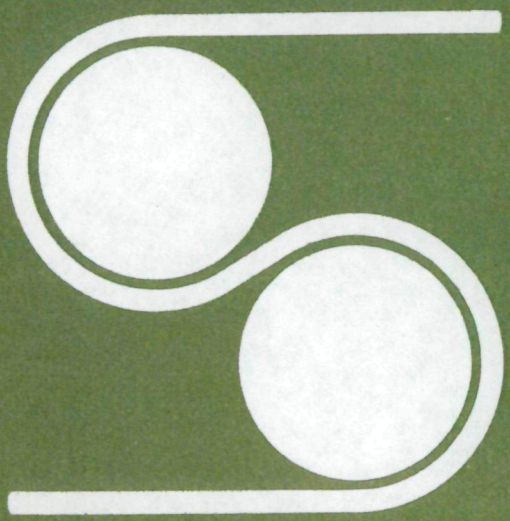

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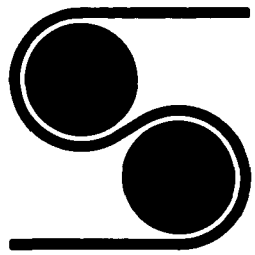

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Albuquerque

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INTRODUCTION

OPENING STATEMENT BY WILLIAM A. SHINNICK
DIRECTOR OF THE TECHNOLOGY APPLICATION CENTER

In the year since its release to the public the rolamite device, invented at Sandia Laboratories, has been given considerable further development. In order to speed the transfer of this new technology to both the private and public sectors of the economy, the Sandia Laboratories Office of Industrial Cooperation and The University of New Mexico Technology Application Center have co-sponsored this two-day symposium.

The Office of Industrial Cooperation (OIC) is funded by the Atomic Energy Commission as a major part of a program to disseminate AEC developed technology for non-AEC users.

The Technology Application (TAC) is funded by NASA and the Department of Commerce to transfer the technology generated through NASA and other government R&D programs to private industry. TAC provides to member companies a variety of technical information services aimed at assisting the member to:

- Find already existing solutions to technical problems.
- Keep technologically up to date in their area of interest.
- Become aware of new innovations and ideas which may have economic significance.

Consistent with these missions, this symposium is structured to provide a maximum amount of rolamite technology in a minimum amount of time.

The first day's presentations will summarize operating principles, design criteria, and basic applications. The second day's sessions will allow the participants to meet in small groups with authorities in the new technology to examine in more detail specific application areas.

William A. Shinnick
Director, TAC

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OPENING STATEMENT BY G. CORRY McDONALD, DIRECTOR OF SANDIA LABORATORIES OFFICE OF INDUSTRIAL COOPERATION

As one of your hosts, the Sandia OIC also welcomes you to this Symposium. The reason for sponsoring this meeting has been briefly expressed by Bill Shinnick. This conference is only one of the several methods which we use to transfer new technology to the public sector. We currently are involved in the transfer of information in at least a dozen other fields which to some parts of industry are even more interesting than rolamite. The literature on these items is available at the registration desks.

We use various means to locate and identify segments of industry which should be interested in specific innovations but we are charged with the responsibility of disseminating such information on a nonpreferential basis as a public charge. The fact that some parts of industry are more sensitive than others to the possibilities and more capable than others of capitalizing on such public information makes our job more fruitful and rewarding. Your coming to this meeting should give you a much better opportunity to use rolamite to your advantage.

Cooperating with us in conducting this meeting are three companies which were early birds in the field. The inventor of rolamite, Don Wilkes, is now associated with a new company called Rolamite Technology Incorporated of Albuquerque. Dr. Lon Bell is the President of Technar Incorporated of Pasadena, California, and Marlin S. Walmer is the Manager of Precision Metals Research Division of Hamilton Watch Company of Lancaster, Pennsylvania. These firms have all obtained licenses to use rolamite in their businesses, and the same opportunities are available to you. The OIC can send you written instructions on how to obtain the cost-free license application, if you decide to proceed. However, until you are ready to use the rolamite in products for sale, you are free to experiment and do whatever R&D in the field that you wish.

In charge of our Morning Program is Bill Shinnick again. We are pleased with your wholehearted turnout. Shall we get started with the program, Bill?

G. Corry McDonald
Sandia Office of Industrial Cooperation

EDITOR'S PREFACE

Two of the papers published in these proceedings are separately published and are available without charge from Sandia Laboratories' Office of Industrial Cooperation. They are Richard V. Cadman's "Rolamite Geometry and Force Analysis" (SC-DC-68-2158), and C. Mark Percival and Frederick R. Norwood's "Theoretical and Experimental Investigation of the Dynamic Response of Rolamite" (SC-DC-68-2202).

Most of the other papers and all the Applications Workshops were taken from taped transcriptions of the proceedings. Particularly in the case of the workshop sessions, these published versions of the tapes can only approximate the discussions. However, I have attempted to retain, in detail, the most relevant and significant points raised.

Preliminary workshop reports were rewritten by the workshop chairmen before final editing, which in some cases was quite severe. My criteria in final editing included relevance and practicality in rolamite application, completeness of useful information presented, and non-duplication. Many of the same topics of concern (e. g., production tolerances for rolamite bands or force generation data) were discussed in several workshops. I have tried to avoid repetition in these cases, which resulted in arbitrary editing of these discussions from one workshop or another. I apologize to the chairmen if these published proceedings do not always reflect the emphases of their discussion.

The success of the conference depended on the work of many people--not only the principals involved in the papers and tutorial sessions, but the nearly 100 participants from across the United States as well. Sandia Laboratories' President John A. Hornbeck's steadfast support for the Symposium was essential to its' taking place. The excellence of the arrangements must be credited to the efforts of William A. Shinnick, who directed the University of New Mexico's Technology Application Center in sponsoring the event. In conception, planning, and in continuing efforts to measure the results of the Symposium, G. Corry McDonald, Sandia Office of Industrial Cooperation, deserves recognition. My personal thanks are due Lee Class and Della Jelski of Sandia's Technical Information Division, for preparing these Proceedings for publication.

Donald Eulert

ROLAMITE PAPERS

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ROLAMITE FUNDAMENTALS

John P. Ford
Sandia Laboratories, Albuquerque

N76-19442

INTRODUCTION

The first speaker of the symposium, John Ford, holds responsibility at Sandia Laboratories for development of rolamite devices. His presentation began with a history of rolamite's development, and proceeded to a discussion of inherent features and capabilities. While pointing out the breadth of applications for the rolamite design, Ford also detailed some basic constraints and limitations of its use.

The text and figures which follow are taken directly from Ford's discussion of a series of 35 mm slides designed to give participants a review of the rolamite mechanical design concept.

HISTORY AND DEVELOPMENT

Rolamite was invented at Sandia Laboratories in Albuquerque by Don Wilkes, whom you will hear later in the program. Don was working on a miniature velocimeter at the time he came across rolamite. He was trying to develop a very small first-integral device (Figure 1) employing a lot of new techniques for miniaturization, such as photochemical processing.

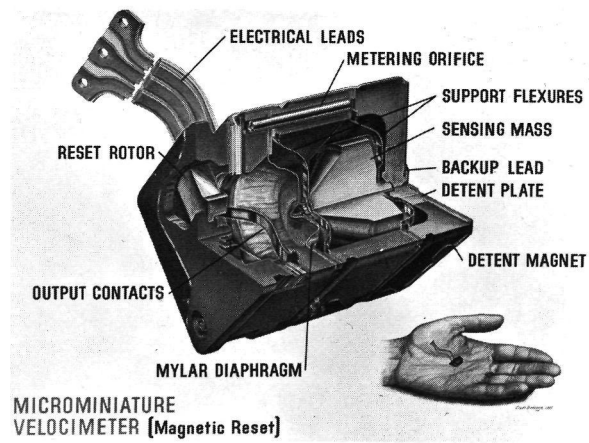

Figure 1

Don was having trouble with the sensing mass, which moved under an inertial load. He could not obtain sufficient displacement of the sensing mass with the suspension system he was using, and he also had some trouble supporting it under side loads. Here we see the system he was using (Figure 2), with the sensing mass, and these are the flexural supports, which had to move in and out as the mass moved.

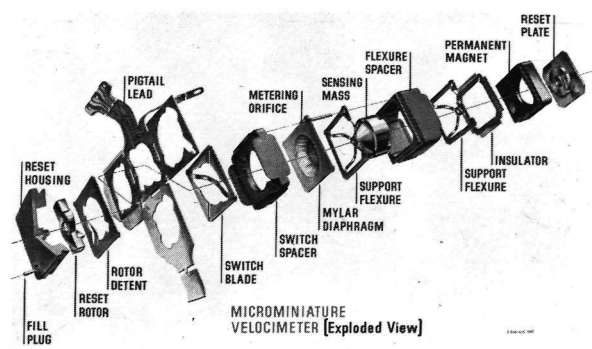

Figure 2

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Under the inertial load, the mass had to move the support members out (Figure 3). He was getting very little excursion of the mass and was having some side-load support trouble.

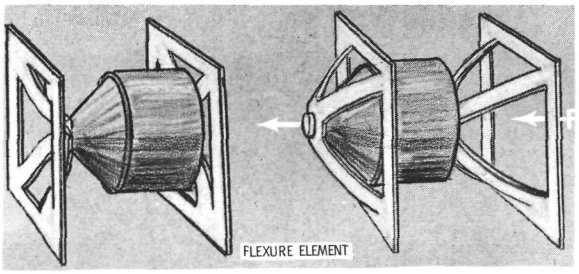

Figure 3

In an effort to get more excursion and better support he happened across the idea of using a thin piece of metal foil bent in an S shape (Figure 4). He found that the band would move very freely back and forth in the X direction but that the side-load support was practically nil in this configuration.

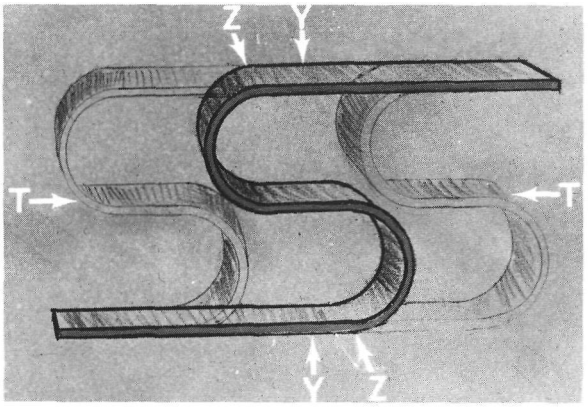

Figure 4

He next inserted a couple of rollers into this S shape (Figure 5); he not only continued to get good movement back and forth but also had started stiffening the whole system.

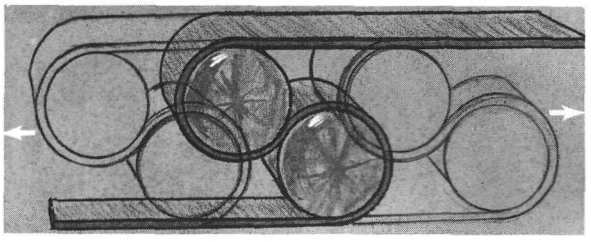

Figure 5

Putting this basic configuration into a case (Figure 6), he found that he had satisfied most of the requirements. The more he started looking at the unique aspects of the geometry, the more he discovered that he had something quite practical and quite new. This, then, is how the concept originated.

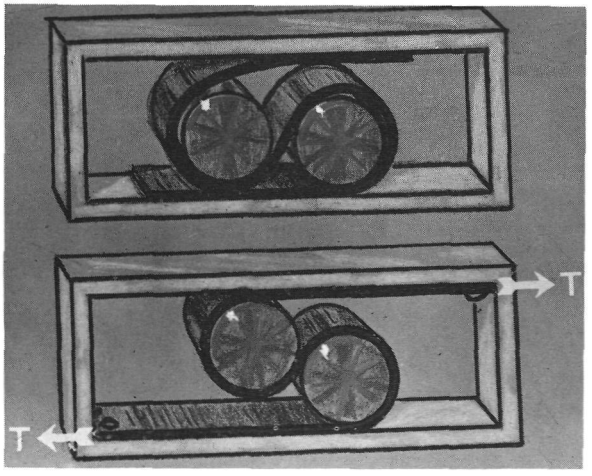

Figure 6

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SUSPENSION SYSTEM FEATURES

Now I would like to talk about some of the features of the rolamite suspension system. First of all, as we said, with this particular geometry you get very free movement back and forth in the X direction (Figure 7).

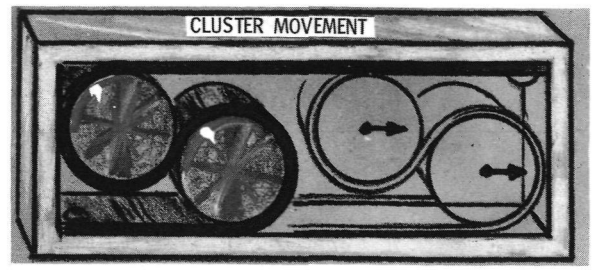

Figure 7

The angle of repose (Figure 8), or the line connecting the centers of the rollers, always maintains the same angle regardless of the location of the roller cluster along its travel. The rollers counterrotate with respect to each other. When they move to the right, the back roller rotates counterclockwise and the front roller clockwise (Figure 9), and they would be just the reverse were they traversing to the left.

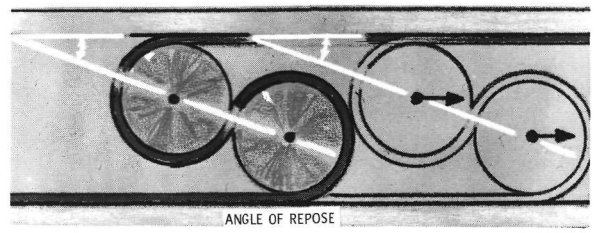

Figure 8

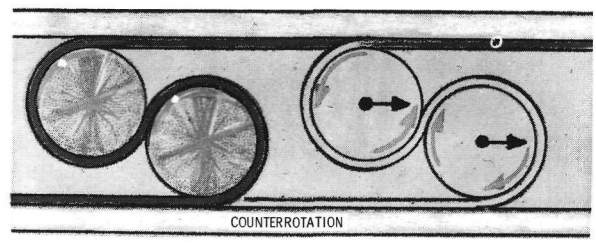

Figure 9

LOW FRICTION FEATURES

One of the two unique things about rolamite is its low friction; here we try to explain why. If you take a point A on the roller and a point A on the band, as shown in Figure 10, the two points will always stay together as the cluster moves. Since there is no relative motion between the band and the roller, there is no sliding friction. The friction is pure rolling friction, which is an order of magnitude less than that of conventional miniature precision roller or ball bearings.

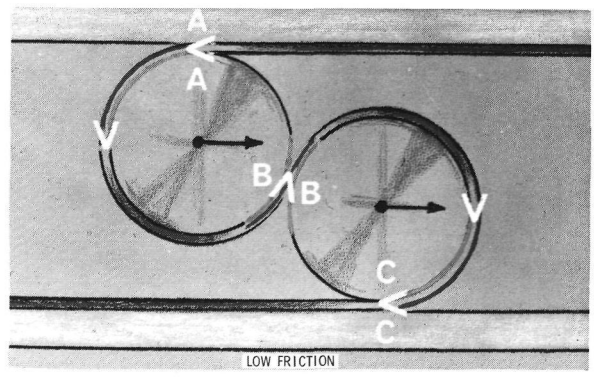

Figure 10

Figure 11 shows some typical friction values that we have measured in some experimental work at Sandia, and you will note that this happens to be for one particular geometry where the rollers were 1/2 inch in diameter and 3/4 inch long, using a beryllium copper band. With various thicknesses of band material, from 1/2 mil up to 2 mils, you will note that the coefficient of friction varies from about 0.0002 to 0.0007.

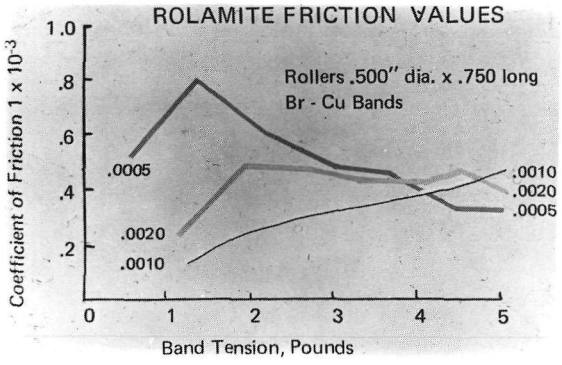

Figure 11

DISPLACEMENT FEATURES

Another feature about the geometry is that the surfaces will always remate once they are displaced from each other (Figure 12). Take a point A on the roller and a point A together on the band and move the cluster so that they will separate; when you move them back, the points will always come together again. This is important because we have found, in testing rolamite configurations, that the coefficient of friction actually decreases with continued wear. By always coming back together, the parts tend to accommodate each other. If there are any imperfections in the band or in the roller, or any contamination, they will wear in together, and continued operation will result in less friction, contrary to what can be expected in most mechanical devices.

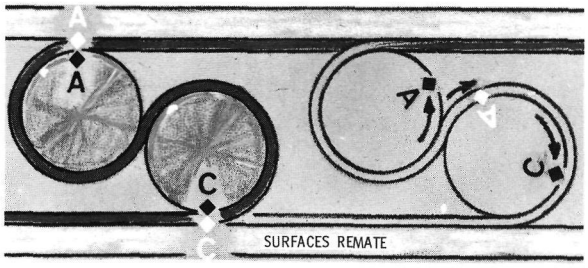

Figure 12

The cycloidal action of the rollers is unusual and gives rise to certain applications. If you have a point A on the band and a point A on the roller, the black, diamond-shaped part will show the trajectory of the point on the roller, and the point on the band will be on the white path as shown (Figure 13). This feature should make for a good dial indicator or speedometer or something of that kind, because a very small lateral movement will give a large sweep of a pointer.

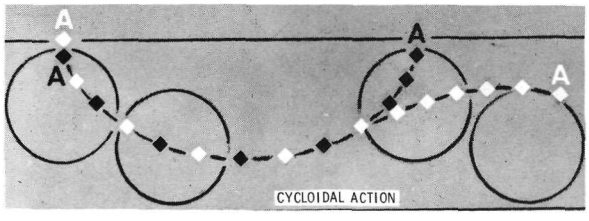

Figure 13

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FORCE FEATURES

Now, I would like to discuss briefly the forces in the geometry. The first force is the tension applied to the band (Figure 14) to pull the cluster together.

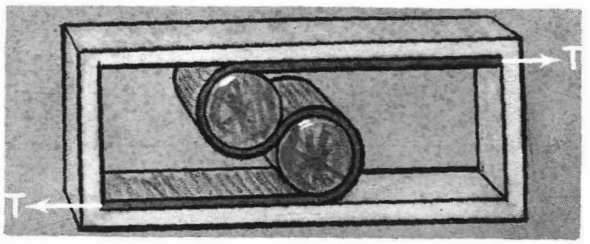

Figure 14

This creates a normal force between the roller and the band, and the band and the case (Figure 15). Taking moments around either of these two points, you will see that the normal force times the distance between the centers of the rollers is equal to the tension in the band times the guide surface spacing: the normal force is equal to the tension of the band times the guide surface spacing over the distance between the centers of the two rollers. This works out to be a very important relationship in figuring out many designs.

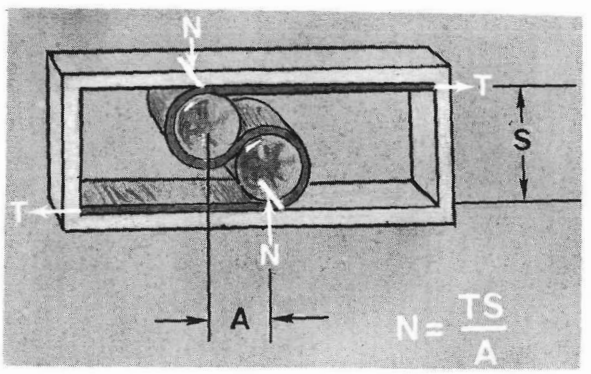

Figure 15

This merely shows that there is a resultant force created by the tension and the normal force, and this is illustrated in Figure 16 by R connecting the contact points of the rollers and the band.

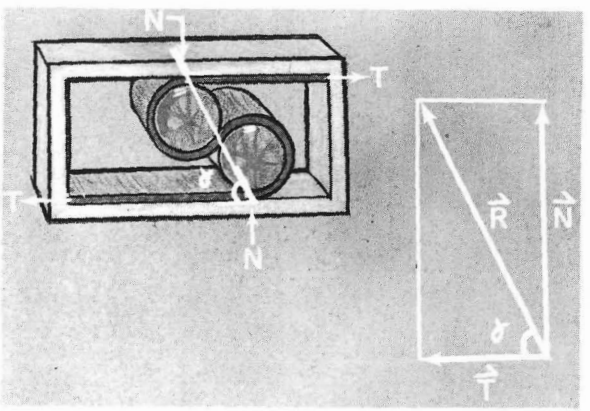

Figure 16

SIDE LOADING

Now let us consider the side-load support. First (Figure 17), in the Y direction we have two conditions (Figure 18), one when the side load is less than the normal force, the other when the side load is greater.

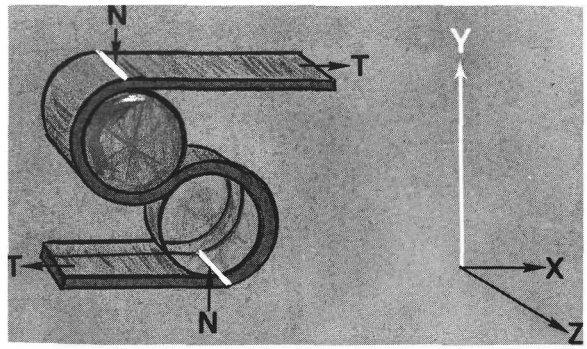

Figure 17

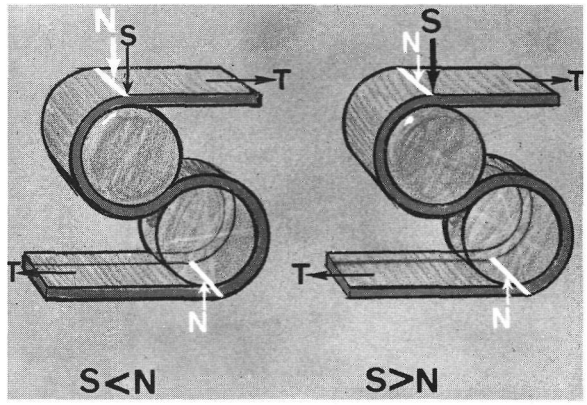

Figure 18

When it is less (Figure 19), the normal force at A will increase, the normal force at C will decrease by the same amount, and the load on the geometry therefore remains constant. There is no roller movement--and no problem.

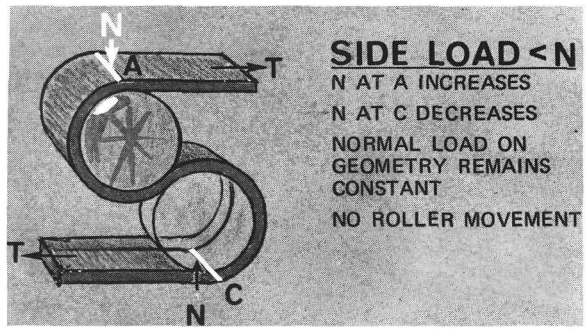

Figure 19

However, when the side load is greater than the normal force, the roller cluster will be deflected (Figure 20), but only as long as the force is applied. Once the force is removed, if you have not yielded the band, the rollers will snap back to their original position. However, if the side load is of such magnitude that you yield the band, then you do have problems and you must therefore design against this condition.

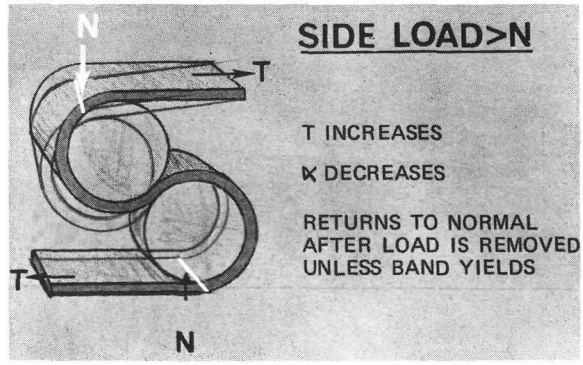

Figure 20

In the Z direction (Figure 21), you get some support from the friction between the rollers and the band, but it is minimal for most applications. In most designs, you have to introduce some friction to give you side-load support in the Z direction.

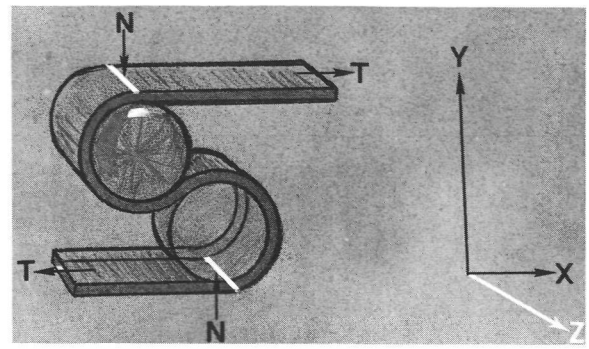

Figure 21

Figure 22 shows several of the many ways of doing it, and a relationship indicating that a good design exists when you can keep X less than 1/30th of the radius of the roller.

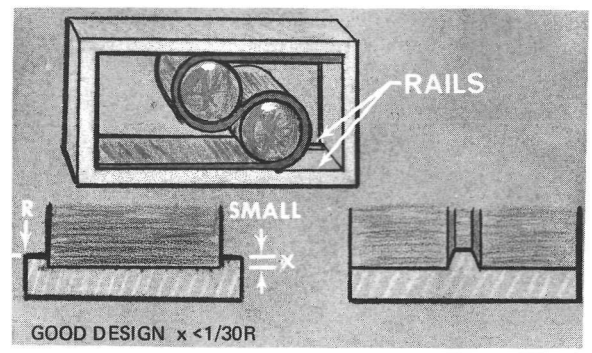

Figure 22

DESIGN CONSTRAINTS

The constraints on the geometry are really quite obvious. Naturally, you have to limit the thickness of the band to be compatible with the diameter of the roller. Figure 23 illustrates an unacceptable relationship and a more normal situation. Again a formula has been derived which says that if you keep the thickness of the band less than the diameter of the roller times the yield stress of the band over the modulus of the band material minus the yield stress, a good relationship between roller diameter and band thickness exists. The next illustration (Figure 24) shows constraints on guide surface spacing with respect to roller diameters and band thickness.

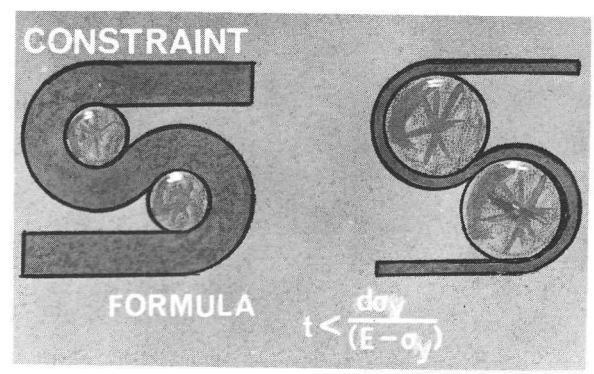

Figure 23

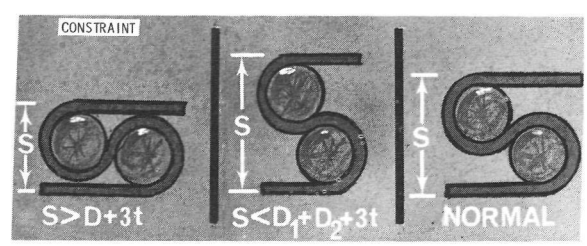

Figure 24

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DESIGN FLEXIBILITY

I would like to point out a few of the things that we believe make rolamite fairly flexible for design purposes. One technique available to the designer is to vary the tension in the band (Figure 25) between a very loose and a very tight geometry.

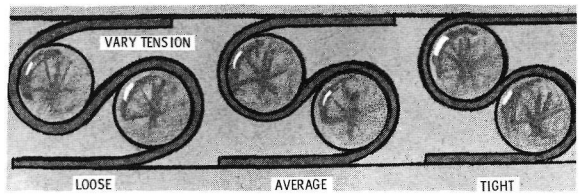

Figure 25

One of the advantages of the loose geometry (Figure 26) is an ability to roll over obstacles such as contamination, lint, or things of that nature that might get between the parts.

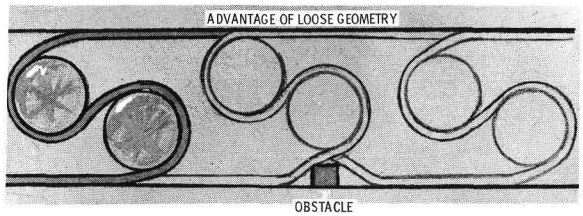

Figure 26

Another thing you can do (Figure 27), given constant guide surface spacing, is to vary the roller sizes and thus change the angle of repose. In each case shown in Figure 27, you will notice that the angle of repose is getting steeper. Therefore, the real variable is the angle of repose.

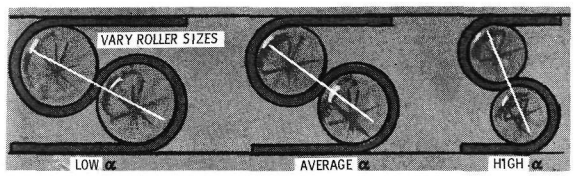

Figure 27

Combining the tension in the band and the angle of repose we have a factor we call compliance (Figure 28). Low band tension and shallow angle of repose result in a very compliant geometry, whereas high band tension and steep angle of repose result in an uncompliant geometry. A very compliant geometry might be useful when you have very small forces to make the cluster move. Or you might have limited travel available but large forces, and would in such a case make the geometry less compliant. You can design to best suit your own situation.

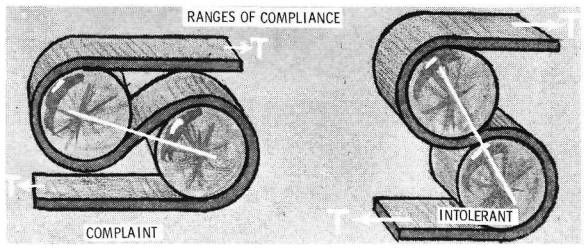

Figure 28

Another thing you can do (Figure 29) is have different roller sizes. The two cylinders need not be of the same diameter. You can use hollow tubing or dumbbell-shaped rollers as shown in Figure 29. If you want a detenting action, you can use flat or cam-shaped rollers.

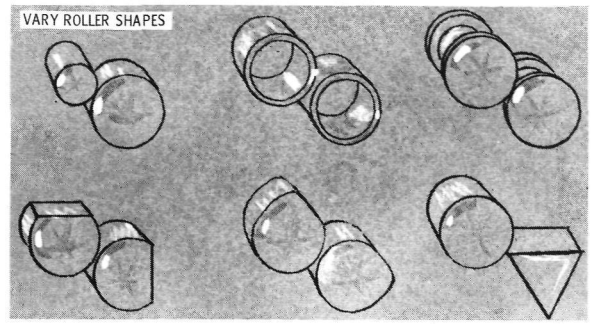

Figure 29

Still another thing you could do is to vary the guide way to provide features that you might like. By putting a groove in the guide surface (Figure 30), you can provide a detenting action, and with a ramp you can provide energy level detenting. With this expanded case you might want the rollers to move down and spring out and provide a latch, or provide some forces in the Y direction. If you want some very peculiar type of curvilinear motion, you might want to design your guide way as shown in Figure 30. Thus, variation in the roller guide-way configurations can provide certain unique design features.

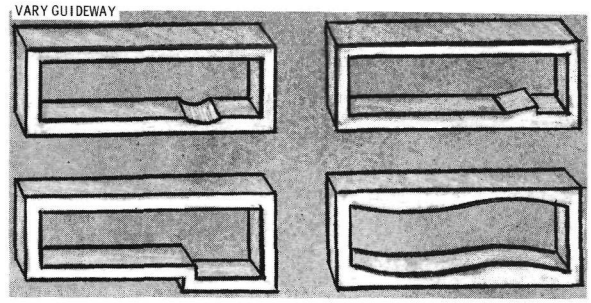

Figure 30

FORCE GENERATION

The next series of slides has to do with the force-generation capabilities of the rolamite geometry. As I said earlier, I think there are two unique things about rolamite. One is the low friction, the other is the ability of the geometry to create forces without additional parts. This may be the most difficult thing to understand, and it will be treated later in great detail by Dick Cadman, but I want to prepare you for his analytical analysis.

If you have a thin metal foil and bend it between your hands, it will assume an S shape, as shown in Figure 31.

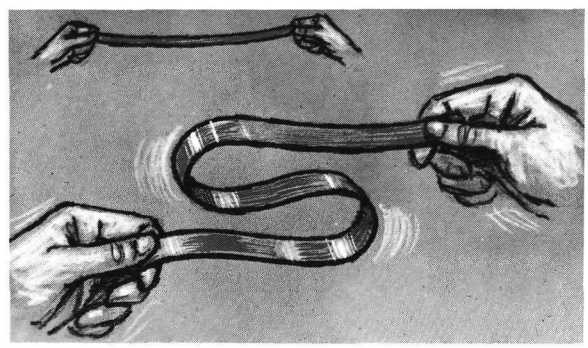

Figure 31

It will then take a force by one of the hands to move it out of that shape. If you notch the foil, it will want to assume the position shown in the blue (Figure 32) and will have created a force to the right in assuming this position. To get it back to the original position would require a force from the man's hand. This really is what happens when we notch bands or change the band configuration in rolamite. The whole force generation capability is brought about by the capability of the band to store elastic strain energy. The area of importance is the working area between points A and C.

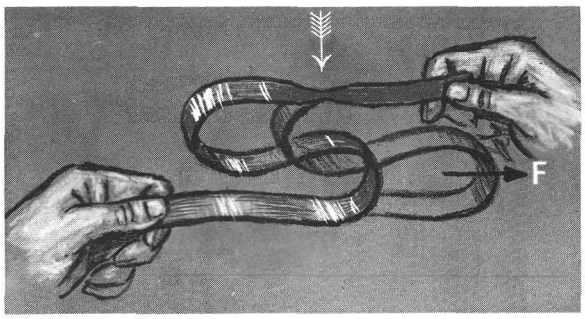

Figure 32

Figure 33 shows a mathematical relationship for the total elastic strain energy in the band between points A and C. This is a general equation which integrates the strain energy in each incremental length of the band times the stress and strain of the band at a distance, y, from the neutral axis of the band times band width. This defines the elastic strain energy available in the band at any one time.

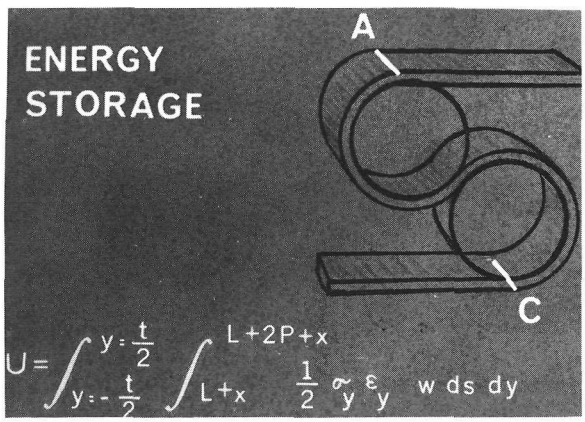

Figure 33

A change in any of the factors in the equation which changes the total elastic strain energy will cause the band to create a force on the roller. Now the way we choose to do this most often is by changing the factor w, or the width of the band.

In Figure 34 we have a condition where everything is in equilibrium between A and C. Since the band is not cut away and is of constant thickness, no forces are created.

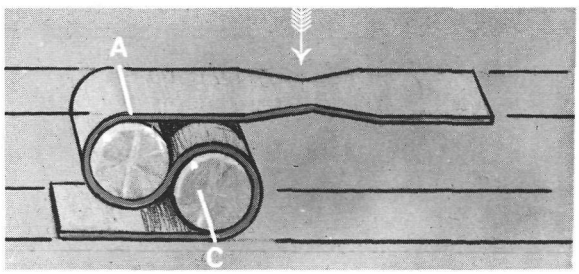

Figure 34

But when the notched-out section of the band (Figure 35) gets to a point over the top roller, then we are going to create a force to the right. The net effect of this in actual operation would be that, if the cluster were moving to the right at a constant velocity and arrived at this notched-out section, the force generated by the band on the rollers would cause the cluster to accelerate to the right. Were it moving in the other direction, the force would cause the cluster to decelerate.

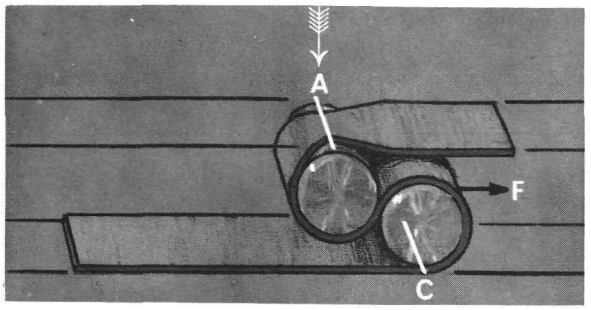

Figure 35

To review (Figure 36), if band widths at A and C are equal, no forces are created; if there is a change in band widths, a force is created.

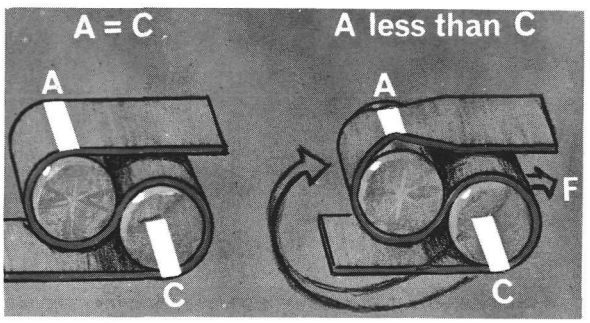

Figure 36

FORCE GENERATION WITH CUTOUTS

There are several ways of configuring a band to get force cutouts. One is an edge cutout, shown earlier; the one we use most often is the interior cutout shown in Figure 37. For a constant force of long duration, you might want to taper a band as shown. I would like to show you a few of the kinds of force deflection curves obtainable by various configurations of the band.

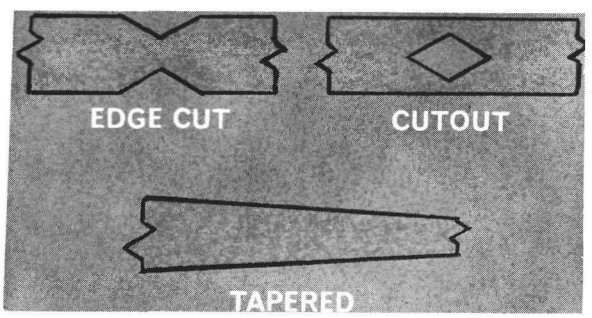

Figure 37

Figure 38 shows a diamond cutout. As the roller cluster first enters the cutout area, a force starts to be created, builds up to a peak at the maximum cutout, and then diminishes. You will note that the force deflection curve is a replica of one half the band cutout.

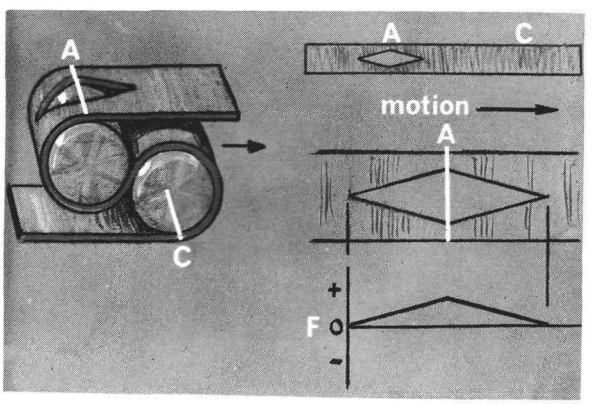

Figure 38

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Figure 39 shows a constant force deflection curve, a negative spring constant which is not obtainable by many other ways, and a step-type force deflection curve.

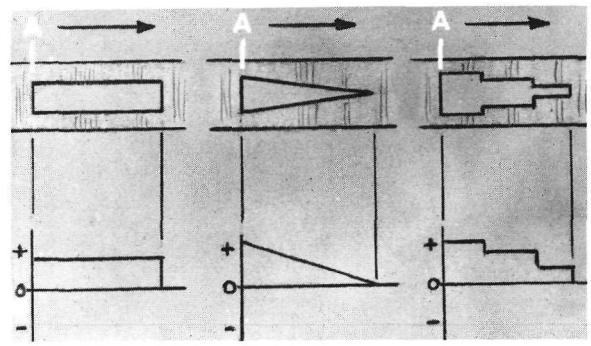

Figure 39

If you want a constant force deflection curve (a constant force for long periods of time), you can taper a band and use it under both rollers simultaneously, as shown in Figure 40.

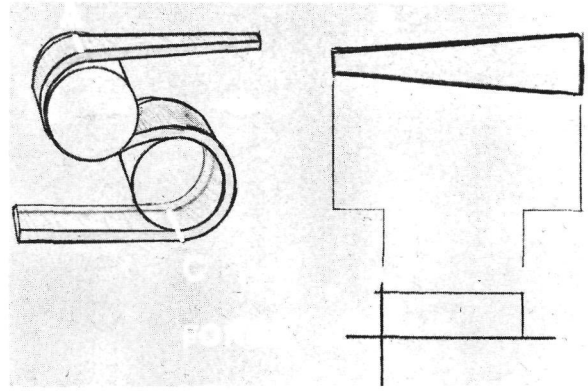

Figure 40

You can also use a cutout under both rollers to provide some unique force deflection curves as shown in Figure 41.

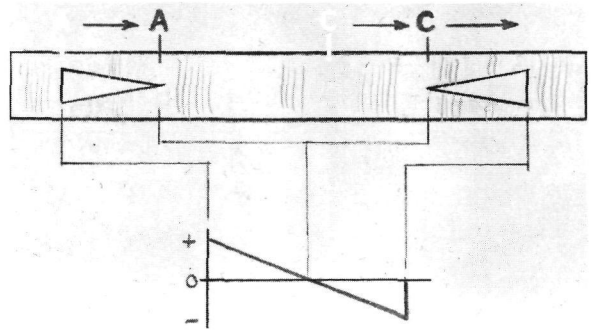

Figure 41

Indeed, you can get all kinds of force deflection curves, depending on how you configure the cutouts, even very elaborate ones as shown in Figure 42.

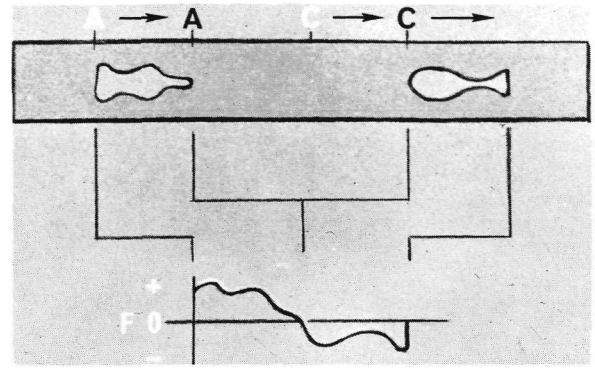

Figure 42

FORCE GENERATION ANALYSIS

The forces generated by the band are more or less illustrated by the equation shown in Figure 43, which is generally correct although it varies somewhat with the looseness or tightness of the geometry. The force generated by the band is equal to the modulus of elasticity of the band material, times the thickness cubed of the band, times the difference in width of the band at points A and C over six times the diameter of the roller plus the thickness of the band squared. A very important factor is the thickness of the band, since it is a cubed factor. You must therefore make sure that your bands are of a constant thickness or you are going to get wide variations in forces.

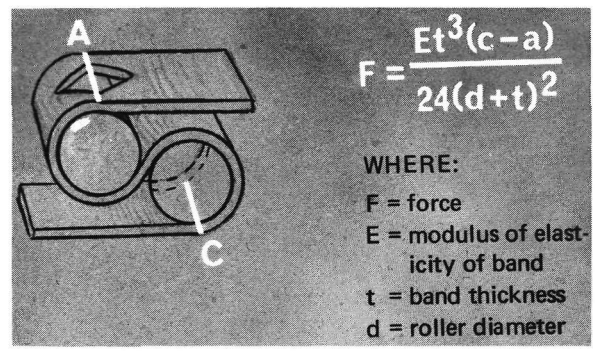

Figure 43

The chart in Figure 44 was drawn up to show the magnitude of the forces obtainable. In our designs we are working with roller diameters of about 1/4 inch and band thicknesses of about 1 mil. For those dimensions, using a stainless-steel band, we can get about 0.14 ounce of force. With a beryllium-copper band, about 0.36 ounce. But notice as you go down the table and get into the larger configurations, up to 2-inch roller sizes and 8-mil bands, that substantial forces can be generated--up to 36 ounces for stainless steel and 92 ounces for beryllium-copper.

ROLLER DIA.	(a - b)	STEEL MAX.BAND THICK.	STEEL F (OZ.)	COPPER MAX.BAND THICK.	COPPER F (OZ.)
.25	.100	.0010	.14	.0017	.36
	.400		.56		1.45
.50	.200	.0021	.56	.0034	1.45
	.800		2.24		5.80
1.00	.400	.0042	2.24	.0068	5.80
	1.600		8.96		23.22
2.00	.800	.0084	8.96	.0137	23.22
	3.200		35.85		92.87

Figure 44

Figure 45 illustrates something said before about the thickness of the band. On an Instron machine we get noise on the force-deflection trace, evidently because the band is not of uniform thickness and thus is responsible for the varying force.

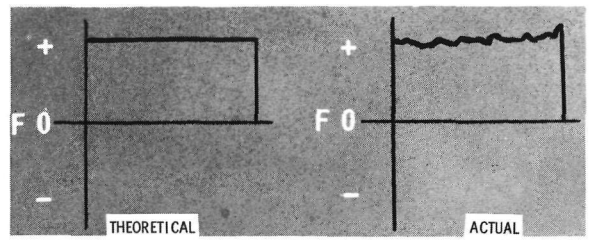

Figure 45

FORCE GENERATION BY PREFORMING

Another way of generating forces with the geometry is to preform the band (Figure 46), in which case we do not change the width of the band, but rather its stress and strain. Shown is the type of force-deflection curve you might get out of a preformed band, but in our experience it has been most difficult to preform bands as opposed to using cutouts in the band to generate forces.

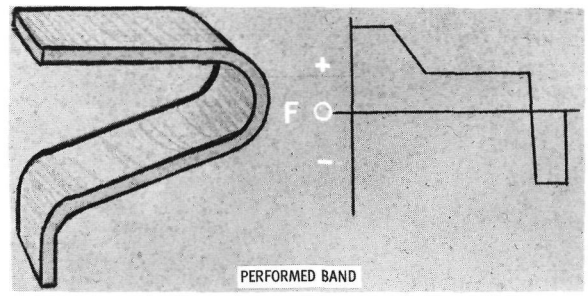

Figure 46

DESIGN APPLICATIONS

Now let me present a few additional rolamite features that can be used in design. If you want to maintain a constant tension on the band, you might want to attach a constant force spring to the band at one end (Figure 47). Or, you might pull off a tongue and put a spring on it. A yoke may be attached to one of the rollers as shown, or a pulley-type arrangement can be designed. Also shown are tabs on the band which are usable for electrical contacting or for latching. Additional rollers in multiples of two and of varying sizes may be used to make up a cluster. They appear to work just as freely as if you had only two.

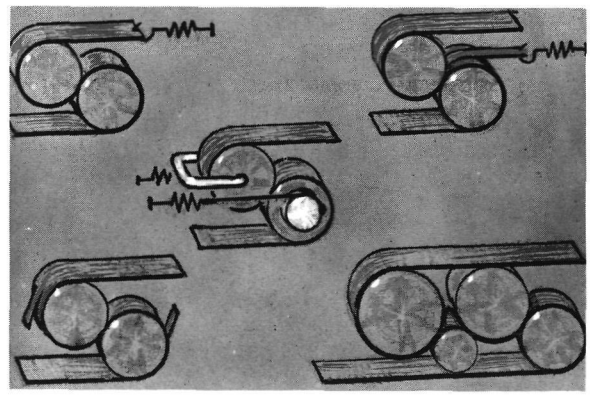

Figure 47

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Figure 48 illustrates a rotary bearing which we think has some potential but requires a fair amount of development work. A model made by Technar seems to work quite well. We do worry about two things, however. One is the band: if you get up to very high speeds, you are going to have metallurgical problems as these thin foils will not stand the loads. There is also a problem in retaining the cluster without introducing some friction. Sandia has done very little with the rotary configuration.

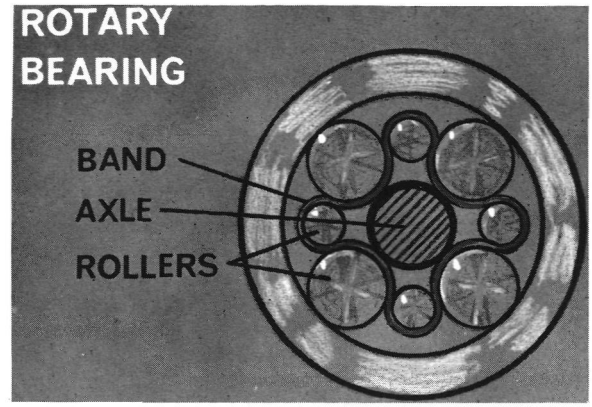

Figure 48

Figure 49 illustrates why we think rolamite can make good electrical contacts. Shown is a band used as a conductor. The tab on the band mates with the contact to complete an electrical circuit. Rolamite offers two unique and very important advantages in making electrical contacts. When the cluster scrubs across the contact it provides an excellent wiping action, and when it rams home it furnishes tremendous contact forces.

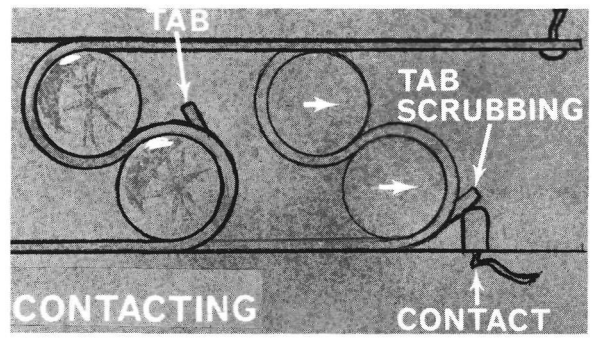

Figure 49

Figure 50 merely illustrates a preformed band, showing that you can carry a number of electrical conductors in a laminated band.

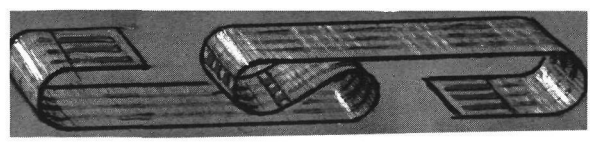

Figure 50

SUBFUNCTION APPLICATIONS

Figures 51, 52, and 53 are a listing of sub-functions that rolamite can perform. If you see some you are interested in, I am sure our panel of experts tomorrow can tell you how to accomplish these functions with rolamite.

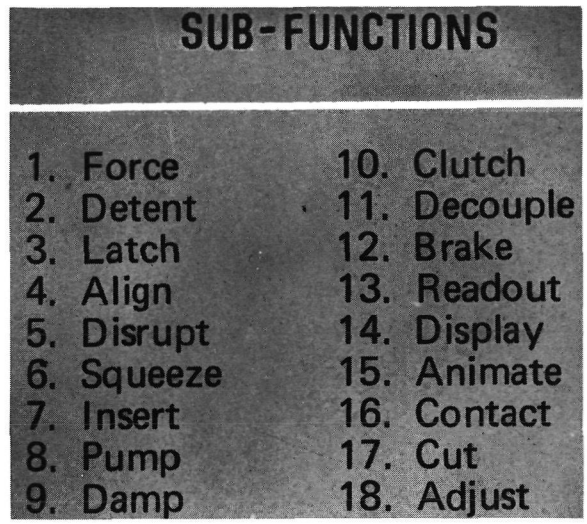

Figure 51

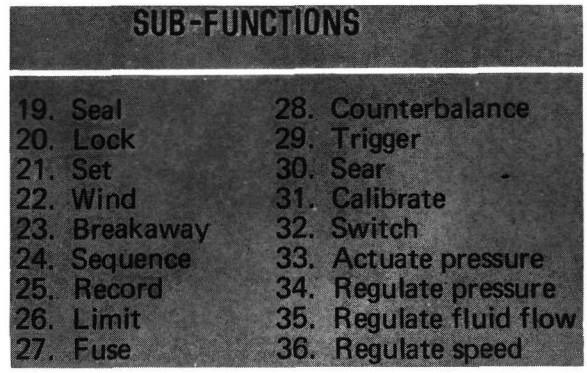

Figure 52

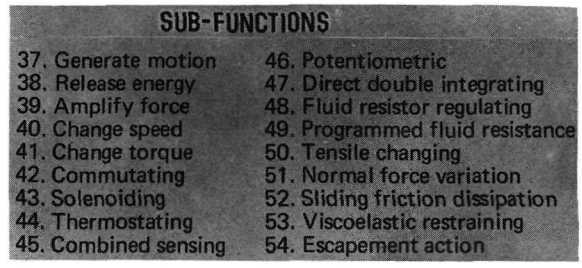

Figure 53

The next series of slides illustrate a few of the functions on the previous lists. Figure 54 shows how you can make an adjustable detent by merely changing the distance that you allow the cluster to fall, into the slot which is controlled by a thumb screw.

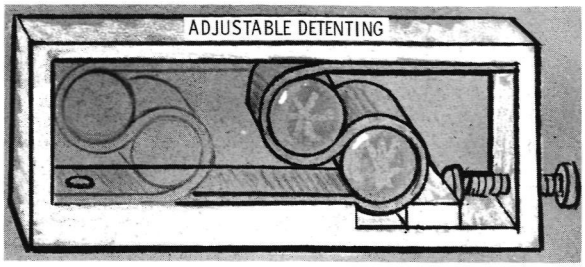

Figure 54

Figure 55 shows an energy-level detenting scheme wherein a certain amount of energy is required for a specific displacement of the cluster and a larger amount for completion of travel.

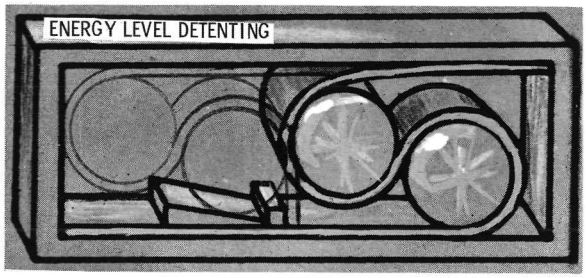

Figure 55

In Figure 56 the cluster moves to the left and, as it comes to the end of the travel, it will snap into position and release large amounts of energy.

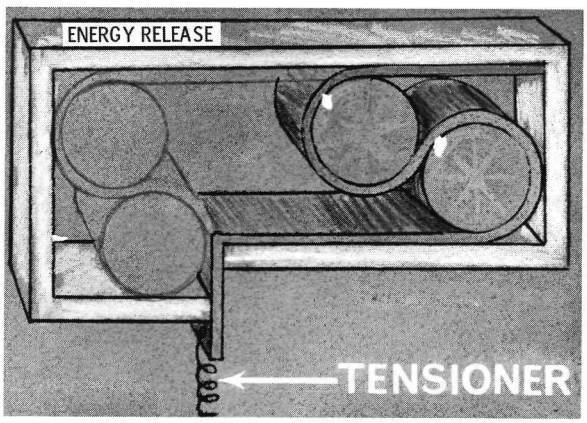

Figure 56

External pumping (Figure 57) can be accomplished by moving the cluster and pumping a fluid or gas contained in the device to the outside.

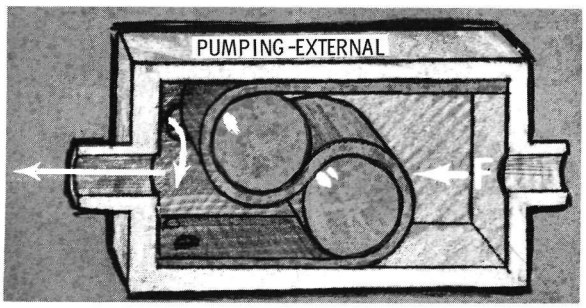

Figure 57

Internal pumping (Figure 58) is an application of rolamite used at Sandia because of our interest in g-second measuring devices. We fill the unit with silicone fluids and, with properly designed orifices, pump them from one chamber to the other. Orificing by the sides of the rollers is possible.

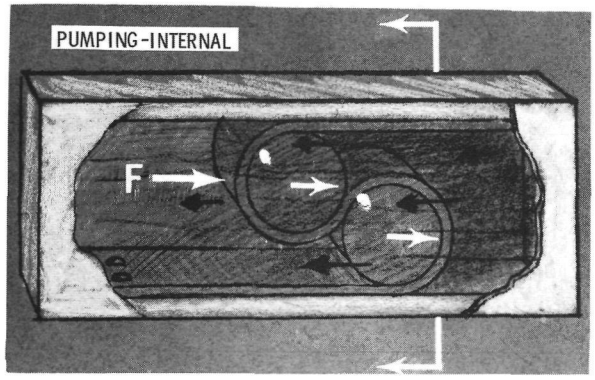

Figure 58

However, we have to maintain very close clearances between the rollers and the outside cases (Figure 59). For gases, we try to keep this clearance between 0.2 to 1.0 mil, and for liquids from 0.5 to 4.0 mils.

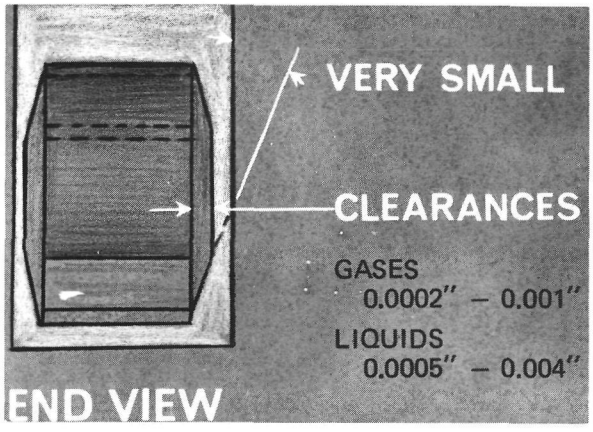

Figure 59

Aligning and disrupting (Figure 60) for ordnance work may be a useful application. If you want to interrupt an explosive train or make an explosive train, you can put the missing link in one of the rollers.

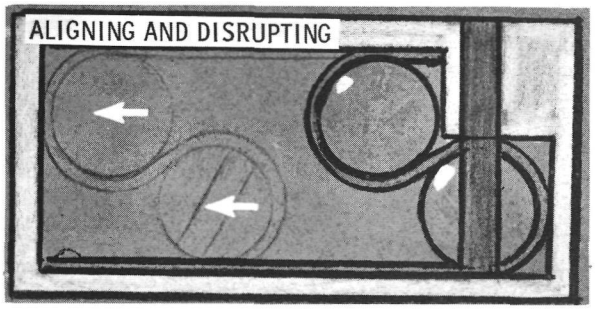

Figure 60

Figure 61 illustrates how you might use rolamite as a valve. With proper design you can get tremendous normal forces for providing a good valve seat.

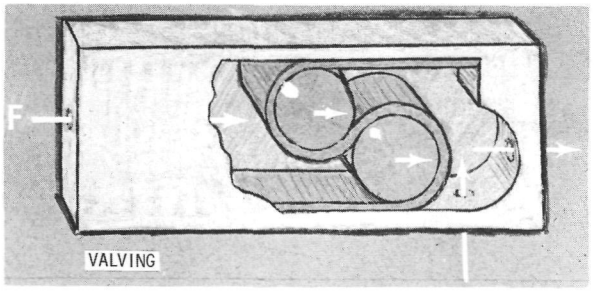

Figure 61

Breaking is illustrated in Figure 62. If you have some sort of frangible vial of toxic gas or liquid you can break it under certain conditions and release its contents. You might encase it between two rollers so that a force applied to the rollers would break the vial.

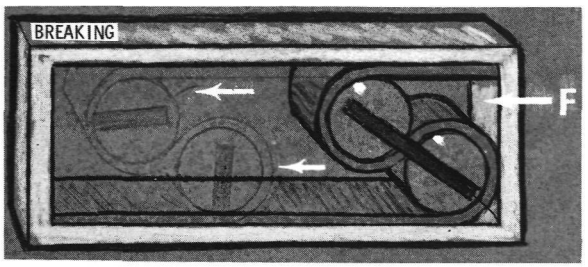

Figure 62

Latching (Figure 63) can be performed very simply by designing a tab on the band. When it comes to the end of the travel, the tab rolls up on the ledge, providing a latching action.

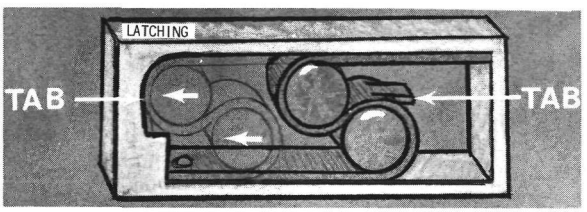

Figure 63

Wedging (Figure 64) can be done in any number of ways; e. g., by putting wedges on the guide surface or on the band.

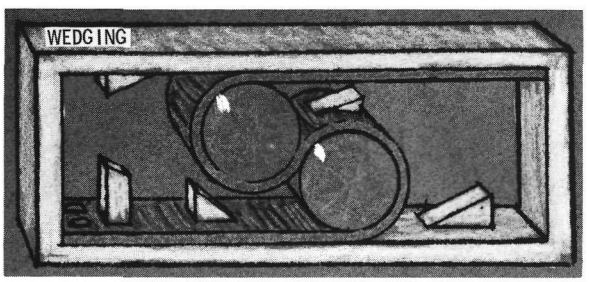

Figure 64

Figure 65 illustrates a simple brake. As you move the cluster, a braking bar contacts the case and causes the cluster to come to a slow stop.

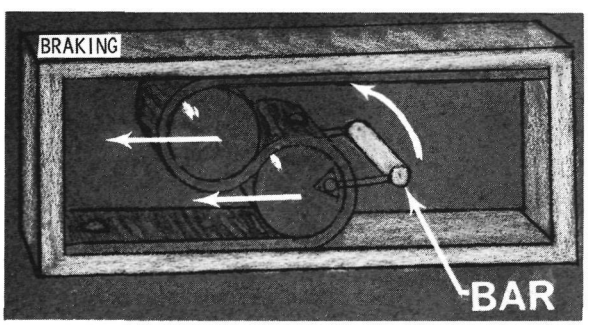

Figure 65

Figure 66 shows a decoupling scheme. If you have a flywheel connected to one of the rollers that you want to decouple at the end of the travel, you let the band expand into the cutout and release the roller from the band, letting the flywheel decouple and come to a slow stop.

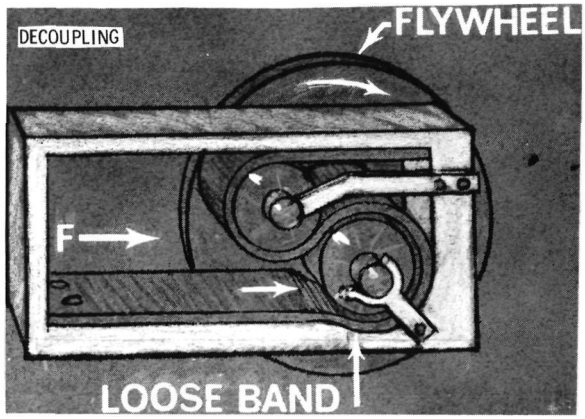

Figure 66

If you are interested in linear speed changing (Figure 67), rolamite is rather unique in that you can get tremendous ratios by using large differences in roller diameters, probably more than you can get in any single stage of conventional gearing. Of course, you are limited by the band-thickness/roller-diameter compatibility problem.

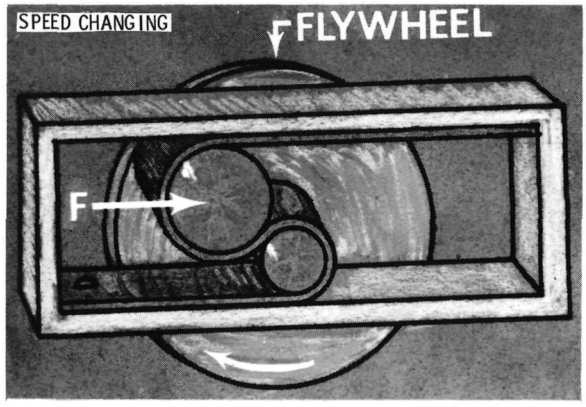

Figure 67

By using bimetallic bands, constructed of low- and high-expansion materials (Figure 68), the cluster can be made to respond sensitively to temperature changes.

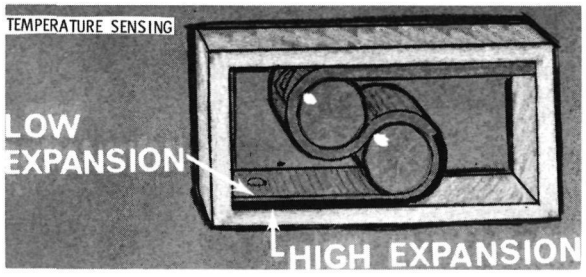

Figure 68

N76-19443

ACCOMPLISHING USEFUL DEVICE FUNCTIONS WITH ROLAMITE

Donald F. Wilkes and Dean Gladow
Rolamite Technology Incorporated

Donald F. Wilkes

INTRODUCTION

Using models of actual rolamite devices, rolamite inventor Donald F. Wilkes conducted a tutorial demonstration of rolamite properties, emphasizing those characteristics which lead to applications. He defines the rolamite design as a superior suspension system with inherent low friction, low energy loss, ease of manufacture, and great design versatility.

The text which follows is taken directly from Wilkes' explanations of how the characteristics being demonstrated can lead to rolamite applications.

ROLAMITE DEVELOPMENT HISTORY

When I was at Sandia Laboratories, the microminiaturization program started in 1962 and took a good deal of effort over a 4- or 5-year span. The modular family of miniature devices that evolved were small in size, about 1/40th of a cubic inch in volume. At the conclusion of the program, we started trying to do a better job in the suspension system, and one of the things of interest was the flat-edge suspension (see Figure 1).

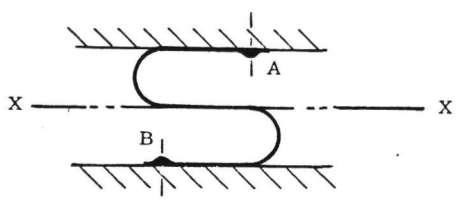

Figure 1. S-Shaped Elastic Suspension

It is very free and a little bit wobbly, not too stable. If you grab hold of it somewhere and roll very far, you will wind up being in one of the lobe areas. The idea occurred to me that if you were to put rollers into the flat-edge suspension you would be able to stabilize this, which is, of course, the origin of rolamite itself. You can see it is a pretty free suspension and it works equally well on the side, upside down, anything you can think of adds a little more realism to it.

Basically, the rolamite is an extremely adaptable, low-friction, suspension system, capable of simultaneously providing (usually with a lot fewer additional parts and a lot less complexity) all of the ingredients needed to build most kinds of mechanisms and mechanical devices. By suspension system I mean that part of a machine that makes the separate moving parts within it behave in a certain way with respect to each other and with respect to ground. So it is really the part of the mechanism that determines the character of the mechanism.

CONVENTIONAL BEARING PROPERTIES

In the broadest sense, a suspension system constrains the parts to behave in the right way. Let me first demonstrate some of these basic characteristics by making comparisons. I am going to use a roller bearing for some comparisons. Now do not misunderstand; I am not saying that I think the rolamite is primarily a bearing, or that it can be compared directly with a roller bearing. I am using this as a way of trying to bring out a different insight into the rolamite itself. First of all, with a roller bearing, you have an inner and an outer race structure, and then you have a lot of cylindrical rollers arrayed between and around the race structure. By definition, these rollers have to be almost identical in diameter or, if you permit them to roll ahead, they will interfere and slide. So a great deal of precision is required to manufacture a bearing or roller bearing or any other kind of a bearing in order to get the rolling elements to cooperate and not dissipate energy by sliding. You usually have to select the diameters, in order to get a successful, cooperating group.

Also, we have the fact that a separator is generally needed. If we took a full complement, an annular region that was completely filled with rollers, unless they were absolutely perfect, and they rolled any distance at all, one would end up pushing against the other and we would be dissipating energy at twice the rate of the forward motion of the rollers because we have one moving down and the other moving up. In order to get around this problem, separators are normally resorted to, which neatly cut the friction in half. But, of course, their mere presence almost makes a lubricant mandatory because you do have sliding going on at very high rates between the rolling elements and the separator.

Another thing that is needed in this kind of bearing is fairly high pressure, because, even though we select the rollers as well as we can to be exactly the same, there are still imperfections and they are not exactly the same diameter. So a rather high force is needed which implies high pressures in the contact areas in order to mash out the irregularities, to mash out the differences between the cylinders and get them to cooperate.

This bearing also has within it an inherent tendency to align itself. The rollers in the bearing want to align themselves with the axis of the inner race and the outer race because the outer race structure is concave and sort of like a ping-pong ball in a dish; if you will give it time, it will settle to the bottom.

In summary, because of the concavity of the outer race, there is a slight tendency for the roller to retain a certain position when it isn't very strong at all. And, because of this, in order to be able to carry any side load at all, the separators are resorted to for additional alignment. Likewise, the rollers themselves must be maintained within certain proportions or they will not be able to bear the side loads well. If they get too long, then they will tip over and continually dig into the surfaces that are needed to hold them in line to keep them running straight and true. As a consequence, we have built-in sources of sliding within this kind of bearing, a definite need for lubrication all the time, and an extremely vulnerable situation as far as wear is concerned.

Any kind of real, live loading situation ends up being somewhat asymmetrical. And so you have a guaranteed source that the separators which are being relied upon for alignment are going to wear asymmetrically and you are going to accentuate the problem with time. Then you are stuck with certain kinds of proportions on the rolling elements just to get them to behave themselves at all. In a bearing like a needle bearing, we find that the rollers are very ill-behaved and in fact, for the average needle bearing, the rolling elements spend their full life at something between 10 and 15 degrees askew with the rolling axis. And energy is being dissipated and the things are wearing out all the time. I am not saying that they are not adequate, but they are not very elegant. Then these kinds of sources of rubbing make the bearings undesirable for precision applications like a head stock in a precision lathe. They are sources of noise and wear which keep these things from running as truly as they might.

ROLAMITE BEARING PROPERTIES

In contrast, with rolamite we have a situation where the rolling process is independent of the roller size, so the size of the rollers does not make any difference and is not going to influence the rolling process. We have had as much as a 300-to-1 difference in diameters and we still get a very good rolling behavior. To do this, we have to have a band that is compatible with the smallest roller; we do not have a situation where the roller diameters have to be selected as any particular diameter in order to roll.

Also, we are guaranteed nonslipping behavior, independent of diameter, by a physical law, which is the law of flexure. When I take a flat, elastic member and bend it, the inner fibers have to shorten automatically to exactly the radius that they occupy in space. And this is the requirement that gives us a nonslipping geometry. The band in a rolamite separates the rollers, but it is a much different beast than a separator in a roller bearing. One of the functions of the band is that it forces; if you can look at the band (Figure 2) and the way it pulls, on, let's say, the metal roller A, you will notice that the forces force this roller into the "v" that is formed between the guide surface and the other roller B, and then in reverse just the opposite is happening on the other roller, so you have a geometry that uses the well-known alignment principle of a "v" guide to align a cylindrical object, and it is a very strong force; in fact, for comparable diameters and lengths of rollers as compared with our original roller bearing we have a difference in this alignment tendency of the order of 1000 to 1.

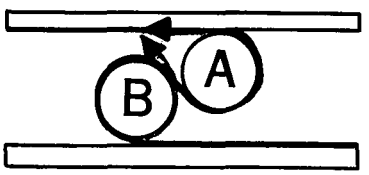

Figure 2.

Now we have a relative minimum but, instead of a shallow dish, we have a very steep energy well and a very strong, aggressive tendency to hold and retain this truly aligned condition. This is an important difference with the rolamite, and, really, is the reason it works well. Do not be misled; if you do a poor job of making the surfaces parallel, or if the surfaces are askew sideways, you have a built-in source that is going to try to tear the suspension apart, so what I say only pertains if the thing is done properly.

We also have provided by the band a traction which keeps these rolling elements from slipping, and it is because of this that the repeatability, after a great number of traverses, is possible. We have a combination of the tensile force and the normal reactive forces occurring to hold these elements in place in the band.

Then we have one other valuable feature coming about because of the band, and this is compliancy. We have two important sources. One is the tensile compliance of the band itself. Here we are comparing a long, relatively low-spring-constant material of the band with a squat object like the roller, which is in both compressions. If you try to roll over a little ramp or particle, the band can accommodate that by merely stretching. I am not talking about strength now; I am just talking about the rate at which force changes with the flexion. Then the second source, in nearly all rolamites that I am concerned with, anyway, is that the tensions we are employing are not so great but that we have some small degree of compliance at the tangent zones. In other words, there is some looseness here which provides a very good functional compliance in making these things work in spite of imperfections that the manufacturing process might introduce (such as lobes or surface roughness).

Another thing that I think is very important in the comparison is the degree of perfection in the rolling process; with the rolamite the process is so much improved that now the need of a lubricant often vanishes. You do not have to have any lubricant at all, or if you do need it, you

are not critically dependent on it. The rolamite can operate for fairly long periods of time, even in a situation where it does need lubrication, without actually degrading too badly. In a roller bearing, because you have to lubricate it, you have energy dissipated by merely pumping the grease or the oil around inside the structure. It is ironical that that energy loss has nothing to do with the prime rolling function. In your car, for instance, there is the case of tapered roller bearings rather than straight roller bearings, but you are paying several cents a mile just to pump the grease around in your front wheel bearings. Because of the lower energy loss, we have less wear, less noise, and less heat, and this sometimes means that you can operate at a higher speed, for instance, because heat is often a dominant factor.

I think the biggest difference occurs in the bearing pressures that are needed to make the bearings behave themselves. There is not a rolling bearing of any kind being used according to the manufacturer's specifications that is not loaded to at least 100,000 psi in the contact zone. The contrast is that the rolamite operates very well, gives you very good behavior, down into the domain of as low as 300 psi--something that I have tested which works very well. I am not saying that that is the absolute lower limit, but at least at that limit it is still working well. This is where the biggest difference occurs. If you are trying to support very heavy loads, this is an insignificant fact; we are not talking about these kinds of pressures. It makes the biggest difference in the field of instruments, because if you are trying to use small ball bearings in an instrument application, you have to load it up to where you have that kind of pressure in the bearing zones just to get it to work. A rolamite device can be built to operate very sensitively with much lower pressures.

The alignment tendency does one other thing for you in the rolamite. It makes it possible for you to take side loads and carry them very well, and to be independent of the proportions of the roller. In rolamite, the wider the bearing the better the alignment tendency of a roller. In the roller bearing, if you are going to have any side load at all, you dare not get the rollers longer than two or three diameters, or they will be unstable. And they are always trying to climb up over the surfaces that hold them in on the end. In the rolamite the alignment is so much stronger that you can very effectively carry side loads with these things. The other fact that has changed markedly is that you can make these bearings as wide as you want to; to carry the load you no longer have to stick to proportions like those in the other kinds of rolling bearing.

In addition, there are two parameters that we can adjust: the tension of the band and the angle of repose. With a fairly low angle of repose the cluster can get over obstacles by merely lifting, decreasing the angle of repose a little bit, and the band can accommodate this. On the contrary, if you go to a very high angle of repose, the cluster becomes friction-locked against side loads or any kind of a change, and actually the band no longer sees any large load, so by this scheme it is possible to take a very thin band and support a very big load with it. It is much harsher, and if you will remember the force relationship, the normal force was equal to the band tension, times the guide surface spacing, divided by the horizontal distance between the center lines. In other words, the normal force N was equal to TS divided by A. You can see that this term S over A is a measure of the angle of repose. As A approaches S, this approaches 1, that is the case where the rollers would be full-sized in the channel, and in this case you have the most compliant geometry of all.

If, on the other hand, you let A go to zero (in other words, you let these things come to where they are almost ready to pass), then you can see that this term can approach infinity, and so for a very light tension you can get a very high normal force. This makes it possible to have great design flexibility; you can make them as wide as you please, you can make them as stern as you please, you can carry any kind of side load you want, because when you go to a high angle of repose, the behavior is very similiar to the load-carrying capability of the roller bearing.

REPRODUCIBILITY OF THE
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ROLAMITE FRICTION AND LOADING

The coefficient of friction is defined as the frictional force measured at one or the other roller centerlines and divided by the normal force; i.e., N is equal to TS over A. Then you can derive that the frictional force is actually going to be just TS over A, times the coefficient of friction, and you see that the friction is then a function of the band tension and the angle of repose times the coefficient of friction. What is meant by "one or the other roller centerlines" is that the rolamite is a case in which you have complete reciprocity; a force that is measured on one of these rollers will be measured exactly the same on the other roller centerline even though the rollers are of different diameters, even greatly different diameters. This is true to a first approximation and it is quite literally true in a tight geometry, so that is what is meant by the frictional force, and we always refer it for ease to the centerline. With the values that we have got, 0.0003 is about the smallest that I have ever seen repeatedly on 1/2-inch-diameter rollers 3/4 inch long. This is sort of standardized to give us something to gather data on that would have some meaning. The very worst that I have ever seen on this size roller is 0.0015, and the average value of all the tests on all materials on the 1/2-inch diameter will be 0.0008. This figure pertains to two-roller clusters; if you add more rollers you have to add more. If you took a four-roller cluster it would be reasonable to double this number. The primary difference, though, comes about in the bearing pressures involved, so the biggest difference between rolamite and conventional bearings comes about in the low pressures required. For instrument and light usage, you are able to use these extremely low coefficients of friction down into pressures as low as 300 psi instead of up in the zone of 100,000 psi, and this is a big difference. Under comparable loads the friction between the rolamite and a regular bearing begin to come together. The residual sources of friction in a regular bearing do not continue to mount with increasing load. So if you load the rolamite heavily enough with a comparable number and size of rolling elements, it would compare very favorably, with possibly a little bit less friction, to a regular rolling bearing, but certainly not be very much different.

SUMMARY OF ROLAMITE PROPERTIES

I have been talking about the suspension aspects of rolamite, and there are three things that are particularly important here. First, we have a very low friction system. Second, we have a system which is compliant and tolerant of imperfections, and variation and contaminations. Third, it is also very adaptable to a wide range of uses. Consider a four-roller cluster. Notice that you can have all different diameters as long as two adjacent rollers meet the constraint that they do not pass each other and still roll. The reason you might want to do this is that it makes it possible to spread out load, distribute load; it makes it possible for you to have immediately available, in coupled form, many different rotational velocities at the same time. The rotary geometries have already been talked about so I will just show you another kind of multiroller situation. This appears to be very nearly the same thing just discussed; the only difference is that it is actually two separate clusters. This brings out another important feature: the rolamite can have as many separate clusters operating in guide channels as you want. These clusters do not have to have two rollers; they can have as many rollers as desired, as long as they are in multiples of two. This is particularly useful, because one cluster can work on the other without any sliding at all, or they can operate independently, anywhere in their travel. One way in which this becomes particularly useful is in breakaway devices; one of these clusters can break away when some particular force level is seen, the other one then can be allowed to come down without any biasing forces of any kind as restrained by a viscous force or some other kind of force.

FORCE GENERATION

By employing a band with a rectangular cutout in it, we can produce a constant force over a limited zone (see Figure 3, Constant Force). If we roll out of the zone where the cutout is exerting an influence, we are back in a neutral geometry again where there is no force. Next consider a spring constant, the same kind of action you get from a screen-door spring if you extend it. Figure 3, Negative Spring Constant, shows this case.

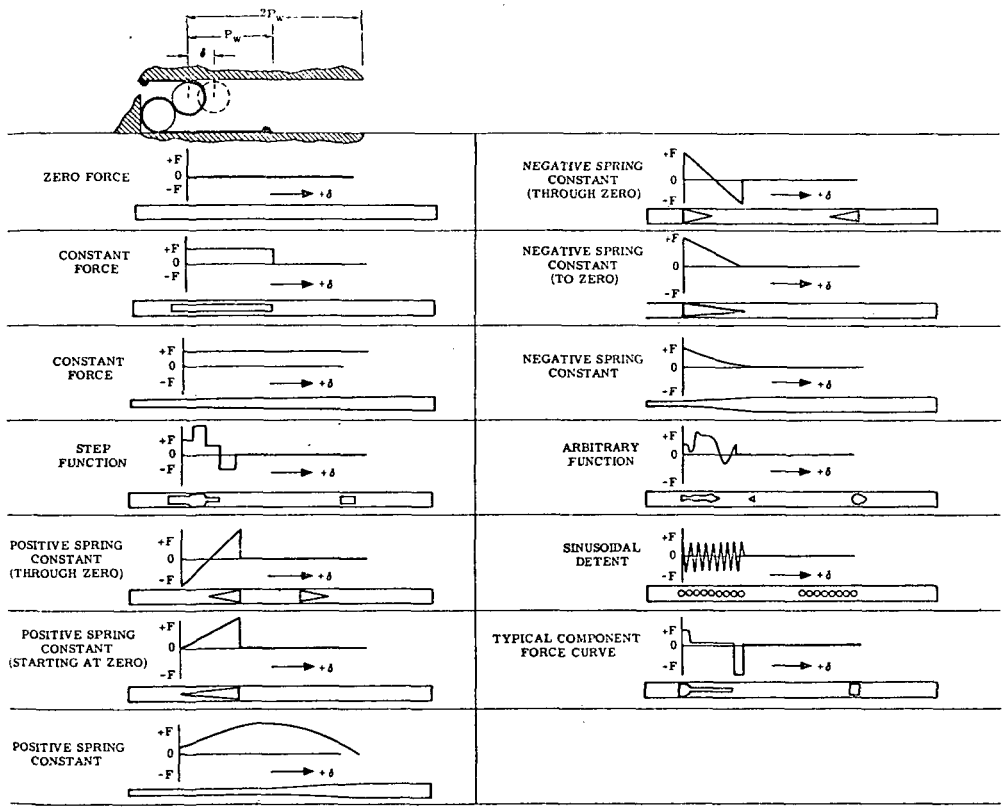

Figure 3. Some Force-Deflection Traces Which Can Be Obtained with Cutout or Tapered Bands

If you want to do some other things with the rolamites, you can generate, by going outside the rolling radius, trochoidal behavior; if you go inside it you generate another kind of behavior which is sort of a watered-down cycloid. By holding one of the rollers stationary and looking at a point on the guide surface you will trace out, by definition, an involute, just like we use in involute profile gearing. If we hold one of the rollers stationary and mark a point on the rolling surface with the other roller it will trace out an epicycloid, and if you permit yourself to go inside the rolling radius on the second roller it will trace out cardioids and all kinds of things; there is just practically no limit to the kind of planar curves that you can generate with this geometry.

ACCOMPLISHING USEFUL DEVICE FUNCTIONS WITH ROLAMITE

APPLICATION CHARACTERISTICS--ROLLERS

Among other characteristics which make rolamite uniquely fitted for a range of applications, note the instantaneous center. You will notice that, at any time, you can consider a roller as pivoting about its outer tangent point, either the bottom roller or the top roller. It then becomes a simple lever and you can think about it for small motions acting just as a lever pivoting about its outer tangent point.

As for reciprocity--any force that is applied at one roller looks as if it was being applied at the other roller. You can measure the same forces one place or the other, and you have two sources, then, that you can get at all the time. Another important thing is the differential behavior of the rolamite, one of the more fantastic things that the rolamite does.

Next, I would like to show you something you can do to change the inertial characteristics. In this case, I think we have an inertial behavior that is about 1/80th of what it should be for the mass of the objects. Now consider a small roller working with a large one. The small roller is fastened to a large flywheel, and you will notice how sluggishly it accelerates. If you are going to build a device and use this, by the time you put a little energy into this thing, you get a horrendous amount of energy stored in this flywheel. So how do you keep the band from breaking? Well, it's very easy in the rolamite, if there is a little detent notch in the upper guide surface. In that case the roller decouples when it reaches the detent.

APPLICATION CHARACTERISTICS--BAND

Now let's just briefly talk about some of the other things a band can do, for example, with short tongues. If we use a band with a short tongue and feed that through between the rollers, we have the basis of providing logic and locking, because the roller will pass over the tongue in one direction, but if we let that tongue come out, now it erects itself and will not go back through. So you see we have it latched and it will not return. There are all kinds of logic and electrical contacting, latching, and other things that can be done with these short tongues. Another possible function is potentiometric. Figure 5 shows how, if you put a resistive pattern down on the band, the roller becomes the perfect contactor, and by wiping down over a segment that has a shape you can profile a resistance chain. Next we have an unusual application based on viscoelastic properties. If you take two layers of band material and put a viscoelastic layer between them, something like double sticky Scotch tape between the two bands, you get a damper that can replace a hydraulic shock absorber or provide viscous delay; it gives you a very true viscous restraint. Also, you can program it by changing the width of the viscoelastic layer; you can program the viscous restraint to anything you want with displacement, and you can provide spring forces at the same time by cutouts in the outer bands.

CONCLUSIONS

I view rolamite fundamentally as a mechanical design technology, one that emanates from a definitely superior suspension system in the first place. It is superior because it has lower friction, lower energy loss; it can do a better job of constraining things to behave the way you want them to, and it is more adaptable. It is appropriate to consider rolamites in virtually anything that has moving parts. Usually the result is a simpler, more foolproof device; this, of course, depends upon the acumen of the one who is doing the design work. But, in general, you come up with a very good result, if you do it well, and if you are not misapplying the principles. It is

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appropriate for anything below, I would say, large earth-moving equipment. I do not believe there is anything in rolamite that speaks to caterpillar tractor treads or anything like this. From things below that size of equipment it speaks very well; there is practically no lower bound at all. We have built rolamite devices with eight thousandths diameter rollers, and they worked very well. Actually, when you are working with the force you can generate relative to the weight of the rollers, you are talking about relatively small devices, just by definition.

N76-19444

THE ROLAMITE—GEOMETRY AND FORCE ANALYSIS[1]

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ABSTRACT

The rolamite is a precision roller-band mechanism which was recently developed. The looseness of the rolamite geometry is a function of the band tension. The tight geometry and the slightly loose (small deflection) geometry may be described by simple equations. Typical digital computer results are presented for the interroller clearance in the very loose (large deflection) geometry.

The rolamite may be made to generate forces if the band flexural rigidity is varied, or if it is precurved. An energy method is used to derive a general form of the force equation.

NOMENCLATURE

A_c = case cross-sectional area, normal to sensing axis
A_e = effective case cross-sectional area, Equation 43
C_L = centerline
d = roller diameter
E = elastic modulus for band material (Young's modulus)
E_p = effective modulus for an infinitely wide plate, Equation 45
F = band-generated force, also the reaction force which balances it
I = moment of inertia for band; for a rectangular band, $I = 1/12\ wt^3$
L = length of band in a transition zone or beam
M = bending moment in band
N = normal component of force acting on band
P = total force (tension plus normal) acting on band
R = effective roller radius
S = effective guide surface spacing
s = distance along band
s_g = guide surface spacing
T = band tension

[1]This work was supported by the United States Atomic Energy Commission.
This paper is based on ASME Paper No. 68-Mech-17, which was presented at the Mechanisms Conference, Atlanta, Georgia, October 6-9, 1968, of the American Society of Mechanical Engineers, and is to be published in the Transactions of the ASME, Journal of Engineering for Industry.

T_m = minimum band tension for a stable rolamite geometry

t = band thickness

U = internal strain energy in band

w = band width

w_c = internal case width

x, y = rectangular coordinates

z = cluster displacement

α = roller angle of repose, Figure 1

β = wrap angle, Figure 2

γ = contact angle (also called force angle), Figures 1 and 4

δ = maximum deflection of a cantilever beam

δ_B = back clearance, i.e., the net clearance or air gap between a roller and the opposite guide (e.g., top roller and bottom guide)

δ_c = chord distance = $R(1 - \cos \theta_B)$, Figure 3

δ_H = vertical distance from root B to tip A, Figure 3

δ_{RN} = net clearance between rollers = $\delta_{RT} - t$

δ_{RT} = total distance between rollers

δ_s = net clearance or "air gap" between roller and guide

ϵ_b = maximum bending strain in band

ϵ_t = strain in band due to tensile loading, Equation 21

θ = slope angle

ν = Poisson's ratio

ρ = local radius of curvature of band, also band precurvature

σ_y = yield point stress for band material

Subscripts

1, 2 = top and bottom roller, respectively

1, 2, 3, 4 = beams 1, 2, 3, and 4, Figure 2

A, B. . . G = points on band, Figure 2

INTRODUCTION

The rolamite is a precision roller-band mechanism with a wide range of possible applications, especially in instruments and miniature mechanical and electromechanical devices. Two of its most important advantages are:

1. The coefficient of friction is low, even with low normal forces or preloads. The cluster has rolling motion with virtually no sliding; lubrication is not normally required.

2. The band can be designed to provide force generation. Cutouts in the band can be used to produce an unlimited variety of force-deflection characteristics.

The most common rolamite configuration consists of a flexible band and two rollers mounted between two fixed, parallel guide surfaces, as shown in Figure 1. The cluster can roll back and forth between the guides, along its "sensing axis."

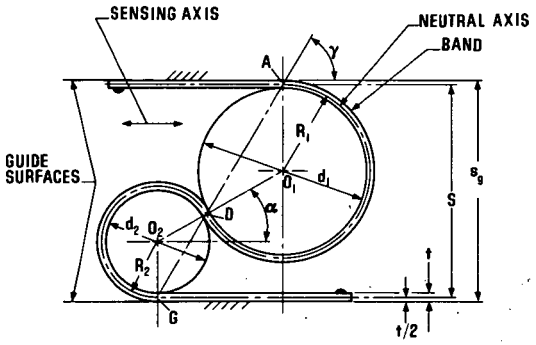

Figure 1. Rolamite Geometry

The rolamite was conceived by Mr. D. F. Wilkes at Sandia Laboratories. His rolamite research report (1)[2] contains analysis, design considerations and variations, an extensive list of applications, and a history of the development of the rolamite. Several articles have appeared in the technical and trade journals (2), (3), (4), (5), (6). The Atomic Energy Commission has applied for patents on the basic mechanism and some applications, in Wilkes' name. Devices covered by AEC patents may be manufactured under royalty-free, nonexclusive, revocable license.

As the rolamite technology developed, it became apparent that certain additional design tools would be useful. Specifically, a method for analyzing the geometry in terms of clearances and band tension was desired. A loose geometry, one with low band tension, as shown in Figure 2, will have very low frictional resistance. The cluster will be compliant and relatively insensitive to surface roughness and contamination. This is especially important in miniature devices. A tight geometry, one with high band tension, is shown in Figure 1. The band holds the rollers securely and there is little chance of misalignment due to shock loading. Also, sharp force-deflection characteristics, such as step functions, are more accurately reproduced by a tight geometry--there is some "rounding off" with a loose geometry.

The rolamite geometry has been analyzed in detail (7). The analysis, summarized in this paper, allows the designer to predict the clearances--or degree of looseness--which will result from a given band tension, or to

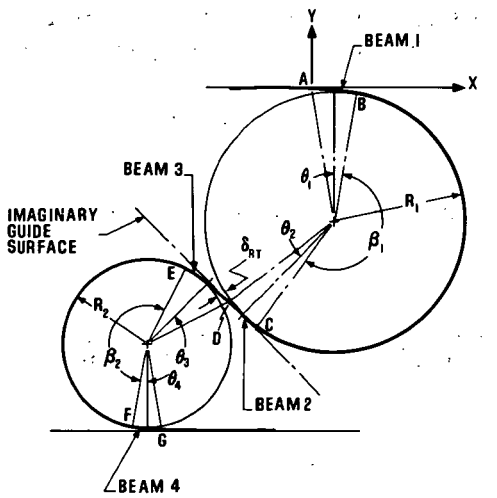

Figure 2. Loose, Nonsymmetric Rolamite Geometry

[2]Underlined numbers in parentheses designate references at the end of the paper.

determine the tension required for an essentially tight geometry. It also permits an accurate determination of band length, even with loose geometries, so that band cutouts and other features may be located properly relative to the various transition zones.

A simple equation can be used to predict the band-generated force for a tight geometry. In a loose geometry, the force is likely to deviate from this nominal value. The geometry analysis allows one to predict the actual band-generated force for a loose geometry.

SMALL DEFLECTION LOOSE GEOMETRY

The effective roller radii and guide spacing, measured to the neutral axis of the band, are

$$R_1 = \frac{d_1 + t}{2} \tag{1}$$

$$R_2 = \frac{d_2 + t}{2} \tag{2}$$

$$S = s_g - t \tag{3}$$

as shown in Figure 1.

Any rolamite must satisfy certain constraints. The roller diameters must be chosen so that the rollers fit properly between the guides. The band thickness must be limited to prevent yielding of the band material when it is bent to the roller curvature.

The loose rolamite geometry shown in Figure 2 can be analyzed by considering the transition zones as cantilever beams. Points A through G are tangency points for the band. Zones AB, CD, DE, and FG are referred to as beams 1, 2, 3, and 4, respectively. At points A, D, and G the band curvature is zero; these points are the tips of the cantilever beams. Points B, C, E, and F are the roots or fixed ends.

A typical transition zone is shown in Figures 3 and 4. In a slightly loose geometry, the deflections are small, and an approximate expression is used for the curvature,

$$\frac{1}{\rho} = \frac{M}{EI} \approx \frac{d^2y}{dx^2}. \tag{4}$$

The bending moment at any point (x, y) on the beam is

$$M(x, y) = Nx + Ty. \tag{5}$$

The bending moment at the root, M_B, causes a curvature in the band equal to the roller curvature 1/R. The cantilever beam equations, for small deflections, are

$$\delta = \frac{M_B L^2}{3EI} \tag{6}$$

$$\theta_B = \frac{M_B L}{2EI}. \tag{7}$$

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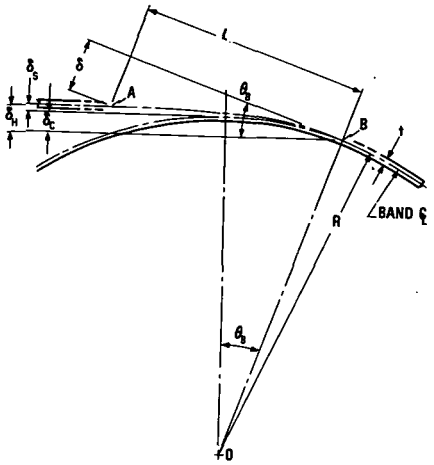

Figure 3. Typical transition zone

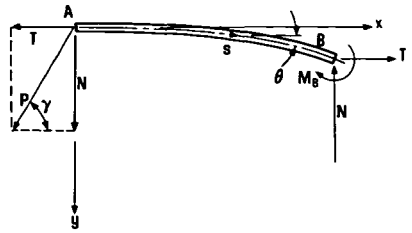

Figure 4. Free-Body Diagram for Typical Transition Zone. (The root or fixed end is at point G, tip is at point A.)

These equations give good results for the rolamite geometry if none of the angles θ_B (i.e., θ_1, θ_2, θ_3, or θ_4) is greater than about 6 degrees. From these equations, for small deflections,

$$\theta_B = \frac{L}{2R} \tag{8}$$

$$\frac{\delta}{L} = \frac{2}{3}\theta_B \tag{9}$$

$$\delta_H = \frac{1}{2}\delta \tag{10}$$

$$\delta_c = \frac{3}{8}\delta \tag{11}$$

$$\delta_s = \frac{1}{8}\delta . \tag{12}$$

Using Equation 8 and Figure 3, one can show that, for small deflections, the beam is centered over the roller center.

There are two cantilever beams between the rollers; their tips touch at point D as shown in Figure 2. From Figure 3, the net clearance between the rollers δ_{RN}, is approximately

$$\delta_{RN} \approx \delta_{H2} + \delta_{H3}. \tag{13}$$

For the symmetric case, equal roller diameters and a neutral band (one having constant flexural rigidity EI), all of the cantilever beams are identical and Equation 10 can be used to show that

$$\delta_{RN} \approx \delta . \tag{14}$$

Thus the clearance or "air gap" between rollers δ_{RN} is about eight times the clearance δ_s between either roller and the guide.

An approximate expression for δ_{RN}, which can be derived by neglecting the Ty term in Equation 5, is

$$\delta_{RN} \approx \frac{1}{3R^3}\left[\frac{EI}{T \tan \gamma}\right]^2. \tag{15}$$

This equation is reasonably accurate for small deflections and small slope angles θ_B. It can also be used to estimate the band tension T required for an essentially tight geometry (e.g., $\delta_{RN}/t = 0.01$).

LARGE DEFLECTION NONSYMMETRIC GEOMETRY

For low band tensions, the rolamite geometry is quite loose and the deflections in the transition zones may be large. Then Equation 4 must be replaced by an exact expression for the curvature

$$\frac{1}{\rho} = \frac{M(x,y)}{EI(s)} = \frac{d\theta}{ds}. \tag{16}$$

Two additional first-order differential equations are required to describe the beam

$$\frac{dx}{ds} = \cos \theta \tag{17}$$

$$\frac{dy}{ds} = \sin \theta. \tag{18}$$

These equations can be integrated numerically for each transition zone. They give the deflection of a beam in pure bending, assuming that the material is elastic. Actually, there will also be some deflection due to shear and tensile stresses, but these are usually negligible.

A digital computer program has been written to solve the large deflection nonsymmetric geometry. It was assumed that all external and inertia forces act through the roller centers and parallel to the guide surfaces, and are in equilibrium with the band-generated force:

$$F_1 + F_2 = F. \tag{19}$$

It was also assumed that the band is not precurved and has constant thickness t and modulus E.

The force analysis and geometry cannot be separated. The two roller free bodies shown in Figure 5 are three-force members. The three forces must intersect at points X_1 and X_2, and the vector sum for each roller must be zero.

The x - y coordinate system has its origin at point A. For convenience in locating band cutout features, the origin for band length, s = 0, is located at the point on beam AB which would be directly above the roller center 0_1 if the band were flat along the guide. (An iteration scheme is used to locate s_A, the band coordinate for point A.)

In order to solve the geometry, values must be assumed for the normal component N_1 of force P_1 and for F. In general, there will be two closing errors, the slope angle at point G and the y coordinate of point G. An iteration scheme is used to improve the assumptions N_1 and F and drive these errors to zero.

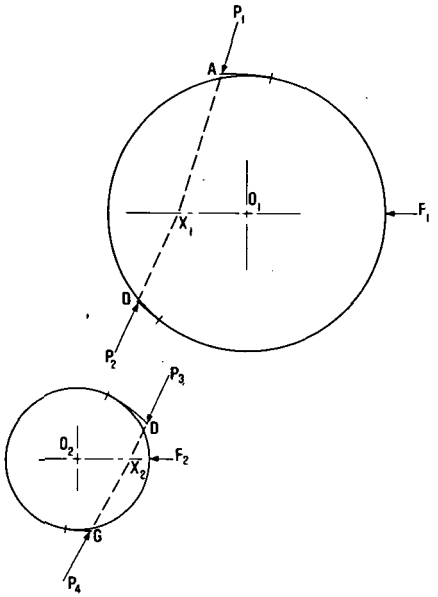

Figure 5. Roller Free-Body Diagrams

Results--Symmetric Case

Three dimensionless ratios can be used to describe the symmetric geometry (equal roller diameters and a neutral band). Additional ratios would be required to describe nonsymmetries, e. g., roller diameter ratio and band width ratios. For the symmetric geometry, the maximum bending strain is

$$\epsilon_b = \frac{t}{2R}. \tag{20}$$

The strain due to the band tension is

$$\epsilon_t = \frac{T}{Ewt}. \tag{21}$$

The guide spacing ratio is, for a symmetric geometry,

$$\frac{S}{R} = \frac{2(s_g - t)}{(d + t)}. \tag{22}$$

Typical results for large deflection symmetric geometries are plotted in Figures 6 and 7. Results from the small deflection analysis, Equation 15, are plotted in Figure 6 for comparison. The dimensionless form of Equation 15 is

$$\frac{\delta_{RN}}{R} = \frac{\epsilon_b^4}{27\,\epsilon_t^2\,(\tan\gamma)^2} \tag{23}$$

where the contact angle γ is used instead of the ratio S/R. For a tight geometry,

$$\frac{S}{R} = 4(\sin\gamma)^2. \tag{24}$$

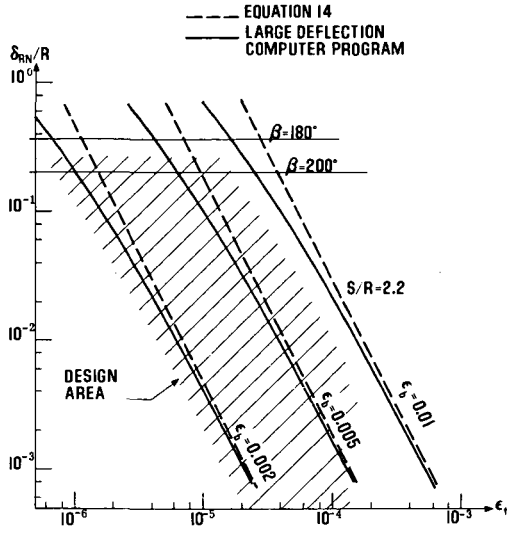

Figure 6. Clearance Between Rollers for Symmetric Geometry

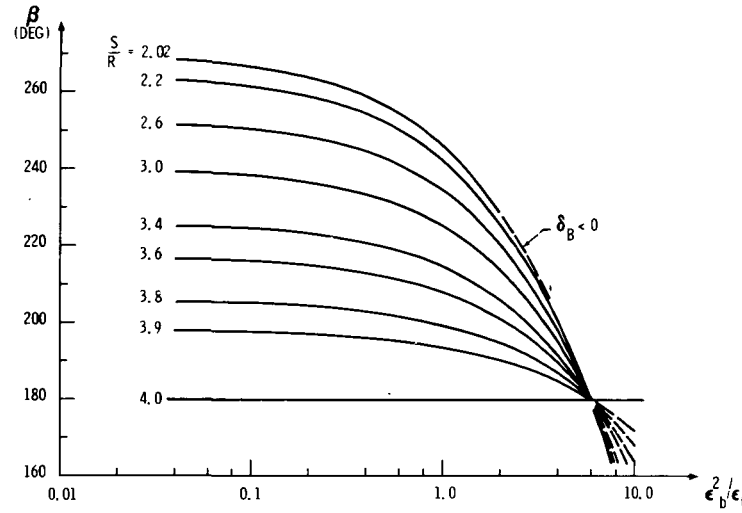

Figure 7. Wrap Angle β for Symmetric Geometries

Actually, two symmetric rolamite geometries having the same numerical values for S/R and ϵ_b^2/ϵ_t will be similar in many ways. Their neutral axes will form geometrically similar curves, and they will have the same δ_{RN}/R, β, γ, etc. Thus, all of the curves in Figure 6 actually are identical in shape. While it is obviously more efficient to use only the two ratios S/R and ϵ_b^2/ϵ_t, a plot like the one in Figure 6 is more convenient for some purposes.

The shaded area in Figure 6 represents the approximate limits for practical designs. The bending strain ϵ_b must be below the yield point. However, a design with a low value of ϵ_b will not take advantage of the force-generation capability of the band material. High values of ϵ_t correspond to high band tension and thus to high normal and frictional forces. The wrap angle β must be greater than 180 degrees or the rollers will not be held securely in place by the band.

The wrap angle β, as determined for a symmetric geometry using the large deflection digital computer program, is plotted in Figure 7. These results show that a wrap angle of 180 degrees occurs at a strain ratio ϵ_b^2/ϵ_t of 6.0 regardless of the guide spacing ratio S/R. This relationship has been verified analytically (7). Stated in terms of dimensional parameters, the band tension for a rolamite device must exceed

$$T_m = \frac{EI}{2R^2}. \tag{25}$$

At a tension equal to T_m the wrap angle β equals 180 degrees and the rolamite geometry is at the point of collapse.

A portion of the curve for S/R = 2.02 is shown dotted and labeled $\delta_B < 0$. For these relatively loose geometries, because of the low S/R ratio, the rollers would be far enough from their own guide to contact the opposite guide surface (e.g., the top roller would be in contact with the bottom guide).

The results of the rolamite geometry computer programs have been verified experimentally. A known band tension was applied, and the clearance between the rollers was measured for several cases. The results show a scatter of up to ±15 percent about the theoretical curve. Sources of error include friction, which may affect the band tension, and thickness variations in the band material. From Equation 15, the clearance between rollers is proportional to the moment of inertia squared or to the thickness to the sixth power. Thus a 2 percent variation in thickness will cause a 12.6 percent variation in clearance. For a 2-mil band, 2 percent of the thickness is only 40 microinches.

GENERATING FORCES

A rolamite device can be made to generate forces. In Figure 8, the external force F balances the force generated by the band. As far as the force picture is concerned, the opposing force F can be applied at the center of either roller. (The point of application will affect the geometry.)

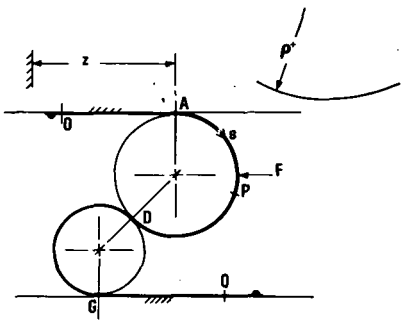

Figure 8. Tight Rolamite Geometry

In Figure 8, assume that the band is stiffer at point A than at D or G. All the band segments will tend to uncurl or straighten, but the stiffer band at A will dominate, and the cluster will tend to roll to the right. To generate a force, the band stiffness or flexural rigidity, EI, may be varied by varying the elastic modulus E, the band width w, or the thickness t. Width variations are the most common. The band can also be precurved to cause the desired force generation.

Castigliano's theorem can be used to derive an expression for the force generated by the band. Strain energy is stored in the curved portions of the band. As the cluster moves to the right, strain energy is released by the band at point A as the band straightens, and energy is absorbed at point G. Energy is released and absorbed at point D, as the band straightens and then conforms to the other roller curvature. If the roller diameters are unequal, the energies released and absorbed at point D, for a given band element, will be unequal.

The elastic strain energy stored per unit length, in a band subjected to pure bending, is[3]

$$\frac{dU}{ds} = \frac{M^2}{2EI}. \tag{26}$$

Let ρ be the precurvature radius, measured to the center of the band. A positive precurvature will be defined as one in which the band is curved toward the bottom roller (roller 2) and away from the top roller (roller 1), as indicated in Figure 8. Assume that ρ/t is large so that the neutral axis of the band nearly coincides with the centroidal axis and the usual flexure formula can be used.[4] Then, to bend the band to the roller radius, a bending moment

$$M = EI\left(\frac{1}{R} \pm \frac{1}{\rho}\right) \tag{27}$$

will be required, where the plus sign is used for roller 1 and the minus sign is used for roller 2.

Assume that the band generates a force by a combination of precurvature and varying width, and that the geometry is tight. If the cluster moves a small distance to the right and static equilibrium is maintained by force F, the cluster must do work Fdz on the opposing force. An equal amount of internal strain energy dU must be released by the band. Thus

$$F = -\frac{dU}{dz}. \tag{28}$$

The minus sign is used because dU/dz is the rate at which energy is absorbed by the band.

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[3] See Reference (8), p. 394.

[4] See Reference (8), pp. 117-122.

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Points O, P, and Q are fixed on the band. Assume that the band width changes suddenly at point P. From Equation 26 the strain energy in band segment OQ is

$$U = \int_0^Q \frac{M^2(s)}{2EI(s)}\, ds. \tag{29}$$

Leibnitz's rule (9) can be used to evaluate dU/dz from Equation 29 provided that the integrand is continuous. The integrand is discontinuous at points A, D, and G because M(s) is discontinuous (assuming a tight geometry--actually, M cannot truly be discontinuous). The integrand is also discontinuous at point P because of the sudden change in width and thus in I(s). To avoid these discontinuities, the strain energy is expressed as

$$U = \int_{s_0}^{s_A(z)} \frac{M^2(s)}{2EI(s)}\, ds + \int_{s_A(z)}^{s_p} \frac{M^2(s)}{2EI(s)}\, ds + \int_{s_P}^{s_D(z)} \frac{M^2(s)}{2EI(s)}\, ds$$

$$+ \int_{s_D(z)}^{s_G(z)} \frac{M^2(s)}{2EI(s)}\, ds + \int_{s_G(z)}^{s_Q} \frac{M^2(s)}{2EI(s)}\, ds. \tag{30}$$

In applying Leibnitz's rule, the integrand is not a function of z so that

$$\frac{\partial}{\partial z}\left(\frac{M^2}{2EI}\right) = 0. \tag{31}$$

The limits s_A, s_D, and s_G all increase linearly with z and

$$\frac{d}{dz}\, s_A(z) = \frac{d}{dz}\, s_D(z) = \frac{d}{dz}\, s_G(z) = 1. \tag{32}$$

The limits s_O, s_P, and s_Q are independent of z so that

$$\frac{d}{dz}\, s_O = \frac{d}{dz}\, s_P = \frac{d}{dz}\, s_Q = 0. \tag{33}$$

If the band is precurved, it may be forced to lie flat on the guides or it may curl away and tend to assume its precurved shape. Assume that it is forced to lie flat on the guides. Thus

$$M(s)\,,\ EI(s)\frac{1}{\rho(s)},\ s < s_A \text{ and } s > s_G. \tag{34}$$

Substituting Equations 27 and 34 into Equation 30 and applying Leibnitz's rule,

$$F = -\frac{dU}{dz} = -\frac{EI(s_A)}{2}\left(\frac{1}{\rho(S_A)}\right)^2 + \frac{EI(s_A)}{2}\left(\frac{1}{R_1} + \frac{1}{\rho(s_A)}\right)^2$$

$$-\frac{EI(s_D)}{2}\left(\frac{1}{R_1} + \frac{1}{\rho(s_D)}\right)^2 + \frac{EI(s_D)}{2}\left(\frac{1}{R_2} - \frac{1}{\rho(s_D)}\right)^2$$

$$-\frac{EI(s_G)}{2}\left(\frac{1}{R_2} - \frac{1}{\rho(s_G)}\right)^2 + \frac{EI(s_G)}{2}\left(\frac{1}{\rho(s_G)}\right)^2. \tag{35}$$

There is no contribution from point P, the width discontinuity. Referring to Figure 2, point A corresponds to the subscript 1, D to 2 and 3, and G to 4. For a tight geometry,

$$I(s_D) = I_2 = I_3 \tag{36}$$

$$\rho(s_D) = \rho_2 = \rho_3. \tag{37}$$

Then Equation 35 reduces to

$$F = \frac{EI_1}{2}\left(\frac{1}{R_1^2} + \frac{2}{R_1\rho_1}\right) - \frac{EI_2}{2}\left(\frac{1}{R_1^2} + \frac{2}{R_1\rho_2}\right) + \frac{EI_3}{2}\left(\frac{1}{R_2^2} - \frac{2}{R_2\rho_3}\right)$$

$$-\frac{EI_4}{2}\left(\frac{1}{R_2^2} - \frac{2}{R_2\rho_4}\right) \tag{38}$$

If the thickness t and elastic modulus E are constant

$$F = \frac{Et^3}{24}\left[\frac{w_1 - w_2}{R_1^2} + \frac{w_3 - w_4}{R_2^2} + \frac{2w_1}{R_1\rho_1} - \frac{2w_2}{R_1\rho_2} - \frac{2w_3}{R_2\rho_3} + \frac{2w_4}{R_2\rho_4}\right]. \tag{39}$$

If the band is initially flat, the precurvature ρ is infinite and

$$F = \frac{Et^3}{24}\left[\frac{w_1 - w_2}{R_1^2} + \frac{w_3 - w_4}{R_2^2}\right]. \tag{40}$$

Note that no force would be generated for the case of constant precurvature ρ, equal roller diameters, and constant width.

These equations can also be derived by force balance methods, but there are some pitfalls. The characteristics of the small deflection geometry must be considered in setting up the free-body diagrams. Brickman's original derivation failed to take this into account (5). Errors have also been discovered in Wilkes' derivation for precurved bands.[5]

[5] See Reference (1), p. 76.

Force Generation With Loose Geometries

Equation 38 was derived for a tight geometry. It is also valid for loose geometries, provided that the precurvature ρ and the inertia I do not have significant variations in the transition zones. Although all band elements in a transition zone of a loose geometry experience changes in stored energy when the cluster moves a small distance, the effect is the same as if one element experienced the entire change.

If the geometry is loose and the inertia I or precurvature ρ varies within a transition zone, the band-generated force will deviate from the nominal value given by Equation 38. In most cases of width variation, the band-generated force can be determined by using the computer program to solve the geometry.

The case of a rectangular cutout provides an extreme example of the errors which can result from using Equation 38 for loose geometries. Typical force traces for a rolamite band with a rectangular cutout are shown in Figure 9. Equation 38 predicts a rectangular force pulse, while the experimental trace exhibits "rise time" and "overshoot." (The band precurvature is zero in this example, i.e., the band was initially flat.)

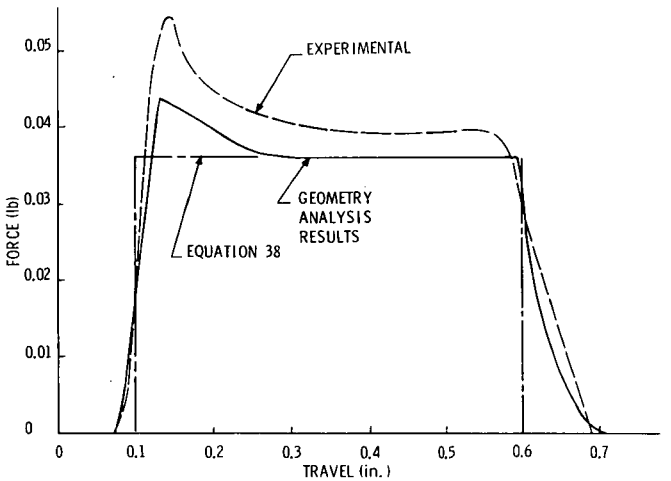

Figure 9. Force Traces for a Rectangular Cutout in a Loose Geometry

The third force trace in Figure 9 was obtained from the geometry analysis computer program. The program required considerable modification before the geometry associated with a rectangular cutout could be analyzed. The rolamite band tends to bulge away from the roller, as shown in Figure 10, at the end of a rectangular cutout. The primary bulge can be explained by some fundamental principles of beam analysis. At the end of a rectangular cutout, the band width changes suddenly, and thus the inertia I(s) has a discontinuity. Then, at that value of s for which I(s) is discontinuous (i.e., at the end of the cutout), some other term in Equation 16 must have a discontinuity. The bending moment, M(x, y), must be continuous; a discontinuity in M would imply infinite cross shear at that point. The elastic modulus E is a constant, and thus the discontinuity must appear in the local radius of curvature, ρ. In the vicinity of the width change, the band radius of curvature is greater than the roller radius on the wide portion of the band, and it is less than the roller radius on the narrow portion of the band. This variation in local radius of curvature can occur only if the band pulls away from the roller and forms a bulge.

As shown in Figure 10, the primary bulge, zone KB, touches the transition zone beam, AK. If the roller moves to the left, from the position shown, the bulge and transition zone will be separated. If the roller moves to the right, the bulge will begin to blend into the transition zone beam, resulting in what might be called a two-contact beam. The ban curvature at the contact point K will be less than the roller curvature. As the roller moves still farther to the right, the contact at point K will be lost, but the resulting transition zone beam will have a width discontinuity, and thus cannot be analyzed as a simple, constant width cantilever.

As the primary bulge KB interacts with the transition zone AK, the strain energy associated with the bulge changes, and thus the force generated by the rolamite is affected by the bulge. The primary bulge must be included in the mathematical model used for the geometry analysis computer program. The details of this analysis are discussed in Reference (7). This analysis was first included in the large deflection computer program, but convergence problems severely limited the success of this attempt. As an alternate approach, the analysis was attempted with the small

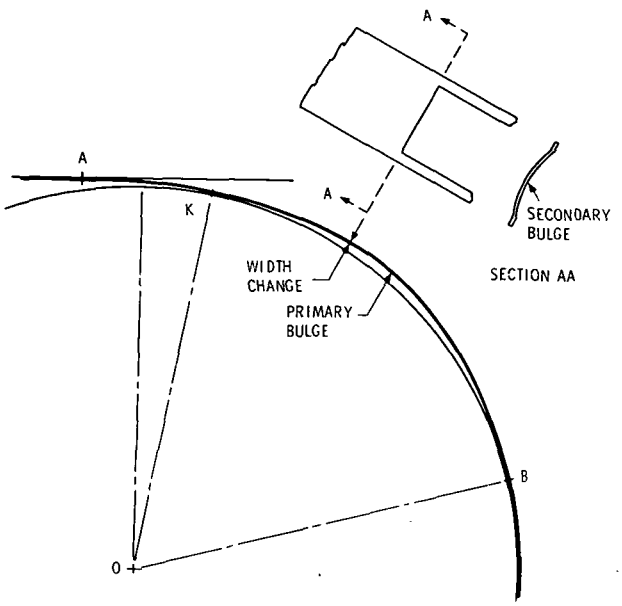

Figure 10. Bulges Associated with a Sudden Change in a Loose Geometry

deflection program. The radial deflections of the band from the roller were treated as small deflections. (The deflection of the band from the guide, at a point such as point B, is certainly not a small deflection.) The small deflection equations for the bulge are algebraic rather than differential equations. They are quite complicated, but can easily be solved on the digital computer.

The third force trace in Figure 9 was calculated using the small deflection geometry analysis program, with the modifications discussed above. This calculated force trace is a reasonable approximation of the experimental force trace. Both have similar "rise times" and "over-shoot." However, the force amplitude in the "steady state" region of the experimental trace is about 10 percent higher than the calculated value. A probable source of this error is a variation in band thickness. The nominal thickness of 0.002 inch was used in the calculations. Since force is proportional to thickness cubed, the 10 percent difference in force levels could be explained by about 3 percent difference in band thickness. A typical manufacturer's tolerance on band thickness is ±5 percent; 3 percent of 0.002 inch is only 60 microinches. Measurement of the band used to obtain the experimental force trace indicated that it was 2 to 4 percent thicker than the nominal value of 0.002 inch.

This point should be emphasized. Use of a band material with a ±5-percent thickness tolerance in rolamite devices will result in a ±15.8-percent tolerance on force levels, unless the devices are somehow individually calibrated.

Note that the force trace obtained from the geometry analysis is in agreement with Equation 38 for many cluster positions. For these positions, the band moment of inertia I is constant within the transition zone, and although the primary bulge may exist somewhere on the roller, it does not touch the transition zone beams.

The secondary bulge, shown in section AA of Figure 10, will also occur at the end of a rectangular cutout. It will cause further changes in the force traces of Figure 9, probably an even higher overshoot and/or longer rise times. The secondary bulge was almost completely eliminated in the rolamite used to obtain the experimental results for Figure 9. This was done by perforating the band in the cutout region with a series of round holes, rather than completely removing the band material in that region. While the effects of perforated bands have not been thoroughly studied, it appears that it is possible to provide a mesh which will essentially eliminate the secondary bulge without reducing the force level significantly. The experimental band used to obtain the force trace in Figure 9 was perforated with rows of round holes on a 45-degree pattern, with about 50 percent of the area removed. For the calculations, a full cutout was assumed. The reduction in force level due to the perforations was too small to be measured, given the uncertainty in band thickness and its effect on the force level.

The secondary bulge has not been analyzed, and is not included in the geometry analysis computer program. Thus, the "overshoot" shown in Figure 9 in the geometry analysis results was definitely caused by the primary bulge, i.e., zone KB.

Force Generation Potential

In most designs, the maximum bending strain due to wrapping the band around the rollers, ϵ_b, is the dominant strain. For example, it is likely to be a few orders of magnitude greater than the strain due to band tension, ϵ_t. Then, as a preliminary design requirement, the maximum bending strain in the band must be below the yield point,

$$\epsilon_b = \frac{t}{2R} \leq \frac{\sigma_y}{E}. \tag{41}$$

Then Equation 40 can be written, for equal diameter rollers and $w_2 = w_3$,

$$F = \frac{Et^3}{24R^2}(w_1 - w_4) < \frac{1}{6}\frac{\sigma_y^3}{E^2} A_e, \tag{42}$$

where A_e is an effective case cross-sectional area and A_c is the actual area,

$$A_e = 2R(w_1 - w_4) \tag{43}$$

$$A_c = s_g w_c. \tag{44}$$

To maximize the force generated for a given A_c, the effective area A_e should be close to A_c, and the bending stress should be near the yield point. Safety factors, clearances, and tolerances must of course be considered. The ratio σ_y^3/E^2 is an index of the force generation potential of the band material.

For a good spring material, $F/A_e = 2.5$ psi is typical. Although this is a low pressure, the band-generated force in small rolamite devices can be large compared to other forces. For example, a band cutout could be designed to detent (prevent motion) 0.23-inch diameter solid steel rollers subjected to a load of 20 g's along the sensing axis.

PLATE EFFECTS

In the foregoing analysis, the band segments in the transition zones were treated as beams. This is a good assumption if the band is not wide compared to its thickness. However, the rolamite band width is often a few hundred times the thickness. For such cases, it is probably more accurate to treat the band as an infinitely wide plate. This can be done by replacing Young's modulus, E, by the effective modulus for an infinitely wide plate, E_p, where

$$E_p = \frac{E}{1 - \nu^2} \tag{45}$$

and ν is Poisson's ratio. Thus, for a given band at a given radius of curvature, the maximum bending stress, the bending stiffness, and the strain energy are all increased by a factor of $1/(1 - \nu^2)$ when plate effects are considered. For a Poisson's ratio of 0.25 to 0.35, the effective plate modulus will be 7 to 14 percent greater than Young's modulus.

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A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE DYNAMIC RESPONSE OF ROLAMITE

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ABSTRACT

In the following paper, Lagrange's equation is used to derive an equation of motion for the rolamite mechanism in the ideal tight configuration; the effects of band inertia, force generation by bands of varying bending stiffness, and nonconservative forces are considered. An experimental system for investigating the dynamic response of rolamite is described. The effects of friction on the rolamite mechanism are discussed and experimentally determined values of coefficients of friction are presented.

INTRODUCTION

Rolamite is a new device having many potential applications in mechanical and electro-mechanical design. Some of these applications have already been realized and many others are currently undergoing development.[1,2] The basic rolamite geometry consists of two cylindrical rollers whose motion is restricted by a thin flexible band and two parallel guide surfaces, as shown in Figures 1 and 2. Under low tension, the system assumes the loose configuration shown in exaggerated form in Figure 1. As the tension is increased, the system finally assumes the tight geometry depicted in Figure 2. In this case, the rollers, band, and guide surfaces are in contact at the points A, B, and C; and the relative motion between the rollers or between a guide surface and a roller is pure rolling. This ideal kinematic arrangement yields a rolling suspension system with no sliding friction, and thus one of the claims made for rolamite is its low friction.

In the tight geometry (Figure 2), normal forces N are needed at the guide surface to establish equilibrium, so the roller cluster is able to support a load perpendicular to these surfaces. The magnitude of this load is proportional to the band tension and is limited by the allowable working stresses in the components. For a uniform band, the potential energy of the assembly is independent of position. However, if the bending stiffness of the band varies along its length, then the potential energy stored in the band will change with the position of the rollers. This change in potential energy induces a force on the rollers toward the position of minimum potential energy.

In the present paper, an equation of motion for the basic rolamite mechanism is derived, an experimental method for studying its dynamic response is described, and experimental results relating band tension to rolling friction are reported.

THEORY

A simple tight rolamite mechanism, as shown in Figure 2, is considered here. The tension in the band is assumed to be independent of time and position, and the rollers are assumed to suffer no deformation. Since the actual system operates at low velocities, wave propagation effects are neglected.

Since the system has dissipative forces, one must use Lagrange's equation in the form

$$\frac{d}{dt}\left(\frac{\partial K}{\partial \dot{q}_i}\right) - \frac{\partial K}{\partial q_i} = Q_i \quad , \tag{1}$$

where K is the kinetic energy of the system, q_i and Q_i are the i^{th} generalized coordinate and force, respectively. The generalized forces may be decomposed into conservative and non-conservative parts,

$$Q_i = - \frac{\partial V}{\partial q_i} + F_i \quad , \tag{2}$$

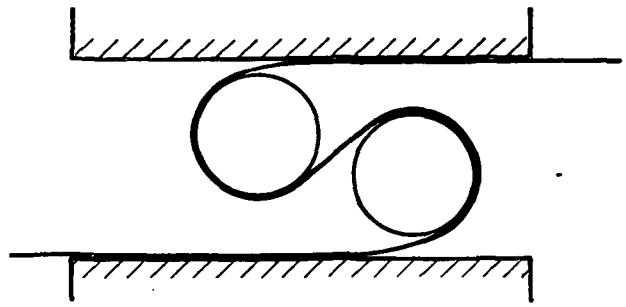

Figure 1. Rolamite Showing Exaggerated Loose Geometry

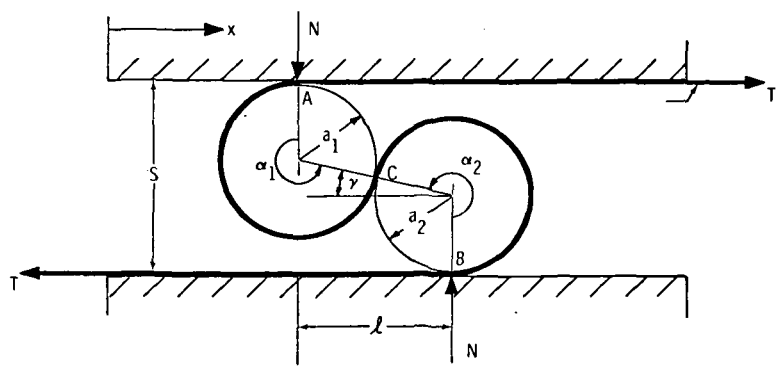

Figure 2. Rolamite in Ideal Tight Geometry

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where V is the potential energy (conservative) and F_i represents the i^{th} nonconservative force. Assuming that the translatory motion is parallel to the x-axis and that no slipping occurs between the rollers and the bands, only the generalized coordinate $q_i = x$ needs to be considered.

Kinetic Energy of the Rollers

The kinetic energy of the i^{th} roller (i = 1, 2) is given by the equation

$$K_i = \frac{1}{2} m_i v^2 + \frac{1}{2} I_i \Omega_i^2 \quad , \tag{3}$$

in which m_i is the mass of the i^{th} roller, $v = \dot{x}$ is the velocity of its center of mass, I_i its moment of inertia, and Ω_i its angular velocity. Since it is assumed that no slippage occurs, $v = \Omega_i a_i$ and, hence,

$$K_i = \frac{v^2}{2a_i^2} \left(m_i a_i^2 + I_i \right) \quad . \tag{4}$$

Kinetic Energy of the Elastic Band

At all times the point A shown in Figures 2 and 3 is the instantaneous center of rotation for the part of the band around the upper roller. Therefore, the velocity of the point P shown in Figure 3 is given by

$$\underset{\sim}{u}(\varphi) = \Omega_1 \underset{\sim}{k} \times \underset{\sim}{r} \quad , \quad \Omega_1 a_1 = v \quad ,$$

where $\underset{\sim}{k}$ is the unit vector in the z-direction. From the figure,

$$\underset{\sim}{u}(\varphi) = - \underset{\sim}{j} v \sin\varphi + \underset{\sim}{i} v(1 - \cos \varphi) \quad , \tag{5}$$

$$\underset{\sim}{u} \cdot \underset{\sim}{u} = 2v^2(1 - \cos \varphi) \quad ,$$

where $\underset{\sim}{i}$ and $\underset{\sim}{j}$ are the unit vectors in the x and y direction, respectively. The kinetic energy of this portion of the band is given by

$$K_{b1} = \int \frac{1}{2} (\underset{\sim}{u} \cdot \underset{\sim}{u}) a_1 \rho_b A d\varphi \quad ,$$

where A is the cross-sectional area of the band and ρ_b is the density of the material of which it is made. Hence,

$$K_{b1} = A \rho_b a_1 v^2 (\alpha_1 - \sin \alpha_1) \quad . \tag{6}$$

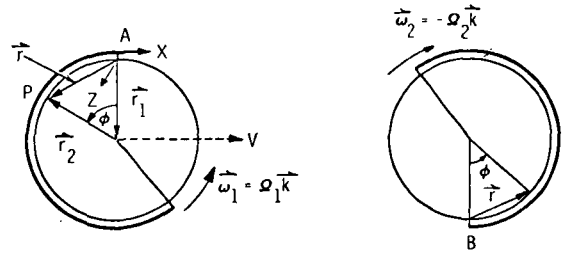

Figure 3. Auxiliary Diagrams for Kinetic Energy Determination

Similarly, for the band around the other roller, one finds that

$$K_{b2} = A\,\rho_b\,a_2\,v^2(\alpha_2 - \sin\alpha_2) \quad , \tag{7}$$

(See Figure 3b).

By adding Equations 4, 6, and 8, one finds that the total kinetic energy of the system is given by $K = I\,v^2/2$ where

$$I = \sum_{i=1}^{2} \left\{ \frac{1}{a_i^2} \left(m_i\,a_i^2 + I_i \right) + 2A\,\rho_b\,a_i\,(\alpha_i - \sin\alpha_i) \right\} \quad . \tag{8}$$

Elastic Energy

In the case of a uniform band, the bending energy and the energy of tension of the band remain constant (say $V_b + V_t = B$) throughout the motion and, therefore, do not contribute to the generalized force. For many applications, bands of variable bending stiffness are required. This variation is usually obtained by punching holes of appropriate shape in the band, as shown in Reference 2. When the band has one of these cutouts, then the bending energy of the band is decreased from its normal value by the energy required to flex a band similar in shape to the cutout. Using beam theory, the energy associated with an element of the cutout of length dx is

$$dV_c = \frac{E}{2} \cdot \frac{b^3 w}{12} \cdot \frac{(d\varphi)^2}{dx} = \frac{E}{2} \cdot \frac{b^3 w}{12} \cdot \frac{dx}{a^2} \quad , \quad w = w(x) \quad , \tag{9}$$

where b is the thickness of the band, w(x) is the width of the cutout, and a is the radius of the cylinder. In Figure 2, the origin of the x-axis is selected to correspond with the start of the cutout when the band is flat on the surface y = h. Thus, in the configuration shown,

$$V_c = \frac{Eb^3}{24\,a_1^2} \int w(x)\,dx \quad ,$$

and

$$V = B - V_c \quad , \tag{10}$$

where B is the energy that would be stored in the band if there were no cutout.

Equation of Motion for the System

When the aforegoing results are substituted into Equation 1, one obtains

$$\frac{d^2x}{dt^2} \cdot \sum_{i=1}^{2} \left\{ \frac{1}{a_i^2} \left(m_i a_i^2 + I_i \right) + 2 \rho_b a_i (\alpha_i - \sin \alpha_i) \right\} = \frac{Eb^3}{24 a_1^2} w(x) + F_x \quad , \tag{11}$$

where F_x represents the nonconservative force. From the first term on the right side, we see that the device produces an acceleration proportional to the width of the cutout.

For very thin bands there is a range of tension wherein the tight geometrical configuration exists; but the normal force at the band-roller interface is insufficient to prevent slippage, and thus the device is loose in respect to some of its kinematical properties. Depending on the coefficient of friction for the band-roller interface, there is a value of tension below which slippage occurs. At this value the relation $V = \Omega_i a_i$ given after Equation 3 becomes inapplicable and must be replaced by $kV = \Omega_i a_i$, where $0 \leq k \leq 1$. As a consequence of this change, I_i should be replaced by $k^2 I_i$ in Equations 4, 8, and 11. The effect of slippage is thus seen to be a reduction in the effective inertia of the device.

EXPERIMENT TO MEASURE FRICTIONAL FORCE

To determine the nonconservative force, it is necessary to appeal to experiments. One may assume that the force F_x depends on (1) hysteresis losses in the flexing of the band, (2) viscous friction, and (3) friction losses at contacting surfaces, including elastic-plastic deformation of band rollers, guide surfaces, and adhesion of contacting materials.

Experimental determinations of the magnitude of band hysteresis losses have shown that in a well-designed device these are negligible when compared to the overall friction of the rolamite mechanism.[3] That the viscous friction is also very slight will be demonstrated later in this paper. Thus, it was concluded that the dominant nonconservative force in rolamite devices of the sort under consideration depends on friction at the contact surfaces and corresponds to a constant value of F_x in Equation 11.

By operating the rolamite under well-defined conditions, it is possible to relate the variation of actual dynamic response from that predicted by a friction-free theory to these friction forces. An experiment was proposed wherein the rollers were allowed to fall vertically under the influence of gravity for a fixed distance. The only variable was the band tension, which influences the normal force and contact pressures in the rolamite.

For the above conditions, the equation of motion takes the form

$$I \ddot{x} = W - F_x \quad , \tag{12}$$

where I is the total inertia of the moving mass, W is the total weight of the moving mass (rollers and band), and F_x is the friction force resisting motion. The moving mass should include not only the rollers and the band on the rollers but also a small portion of band of length ℓ shown in Figure 2. This portion of band will undergo effective translation with a corresponding decrease in potential energy due to the downward motion of the roller cluster with the rolamite in the vertical orientation. If the friction force is constant in a given test, the acceleration will also be constant, but will be less than the frictionless ideal case. By measuring the time required for the rollers to fall a fixed distance, the acceleration can be determined. The weight and inertia of the moving mass are known and the friction force can be calculated from Equation 12. The coefficient of friction f was chosen to be the ratio of the frictional force to the normal force between the rollers and the guide surfaces.

Experimental Technique

The displacement history of the rollers was obtained by optical means, thus avoiding the introduction of external forces that could influence the motion of the system. An overall schematic of the experimental setup appears in Figure 4. A light source provides a uniform and

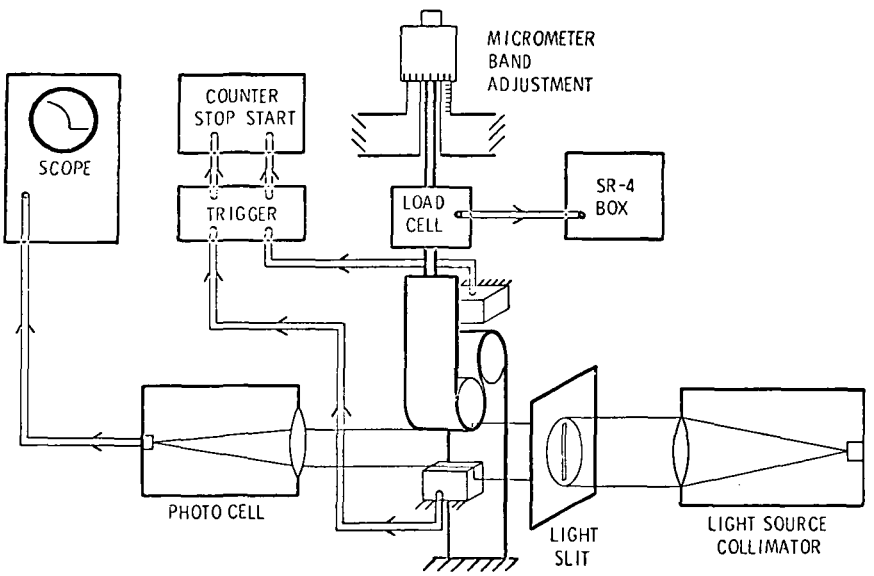

Figure 4. Schematic Representation of Experimental Arrangement

parallel beam that passes through the rolamite and is focused onto a photocell. As the rollers travel along the axis of motion, the light beam is blocked and its intensity, as measured by the photocell, is proportional to the displacement of the rollers. This system was calibrated by closing the light slit with a shutter attached to a micrometer. The calibration data, as well as the rolamite displacement data, is recorded on an oscilloscope and reduced by means of an optical comparator. A computer program was written to correct the rolamite displacement data for nonlinearities in the optical transducer system.

The rollers are initially held against an upper stop by means of a bracket that catches an extension on each end of the upper roller. To release the rollers the bracket is withdrawn by means of an electrical solenoid. Both the rollers and the upper stop are sufficiently rigid that no significant elastic energy is released upon separation. Trials have shown that the response of the rolamite is independent of the initial force between the roller and the upper stop.

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The action time required for the rollers to fall a fixed distance is measured independently of the displacement history. An electrical circuit using a low voltage capacitor trigger provides a microsecond long pulse to start a time interval counter when the contact between the upper roller and the upper stop is broken. When the lower roller strikes a lower stop, the trigger circuit provides an electrical pulse that stops the counter. The lower stop is adjustable so that the distance that the rollers are allowed to fall can be accurately controlled.

The lower end of the band is rigidly fixed to the rolamite frame while the other end of the band passes through a slit in the frame and is attached through a load cell to a micrometer adjusting stress to enable precise adjustment of the band tension. The load cell incorporates a strain gage instrumented cantilever beam as the sensing element and has an upper load limit of 10 pounds. When initially installed or adjusted, the band tension is nonuniform due to the band being loaded by static friction at the contact points. Before collecting data in any given configuration, care was taken to ensure a uniform band tension. This was achieved only by moving the cylinders up and down several times. To demonstrate that the tension becomes uniform, the rigid lower attachment was replaced by a hanging weight. When the weight was first attached to the band, the load cell did not register any tension in the upper part of the band. After several cycles of operation, the tension in the upper part of the band, as measured by the load cell, was within 2 percent of that in the lower part of the band.

Configuration

The rolamite configuration chosen for the initial experimental studies employed hardened steel rollers and guide surfaces. The rollers were 0.500 inch in diameter by 0.750 inch long. For holding and positioning purposes, small extensions 0.125 inch in diameter by 0.125 inch long were made on each end of the rollers. The guide surfaces were 1.00 inch wide. Beryllium-copper foil was chosen as the band material and four thicknesses ranging from 0.0005 to 0.0020 inch were used. The foil, which has a Young's modulus of 17×10^6 psi, was heat treated to a hardness of RC 37-41, which corresponds to a yield stress of 140,000 to 170,000 psi. Bands of uniform cross section were used during this study; thus, $w(x) = 0$ in Equation 11. The distance S between the guide surfaces was fixed at 0.625 inch plus the thickness of the band being used.

This configuration was chosen to be representative, both in size and materials used, of those which seem most likely to find application in precision instruments and similar designs. The beryllium-copper band is known to have low hysteresis losses. The maximum calculated stress in the band due to combined tension, bending, and contact stresses at maximum band tension occurred in the 0.002 inch band and was less than 50 percent of the yield stress for berylliumcopper.

To confirm that the rollers did experience approximately constant acceleration, the displacement history was measured using the optical diagnostics. Figure 5 shows an example of the experimental displacement history and a comparison to theoretical results for $F_x = 0$. The results shown are for a 0.0005 inch thick band and a band tension of 0.30 pound. At this tension, no slipping occurs and the friction force F_x is small since the normal forces are low. The low magnitude of friction force is demonstrated by the close correspondence of the two results. The good agreement between the two results also demonstrates that the rolamite system has very little viscous friction, which would be independent of band tension and most evident in cases where other forms of friction are low.

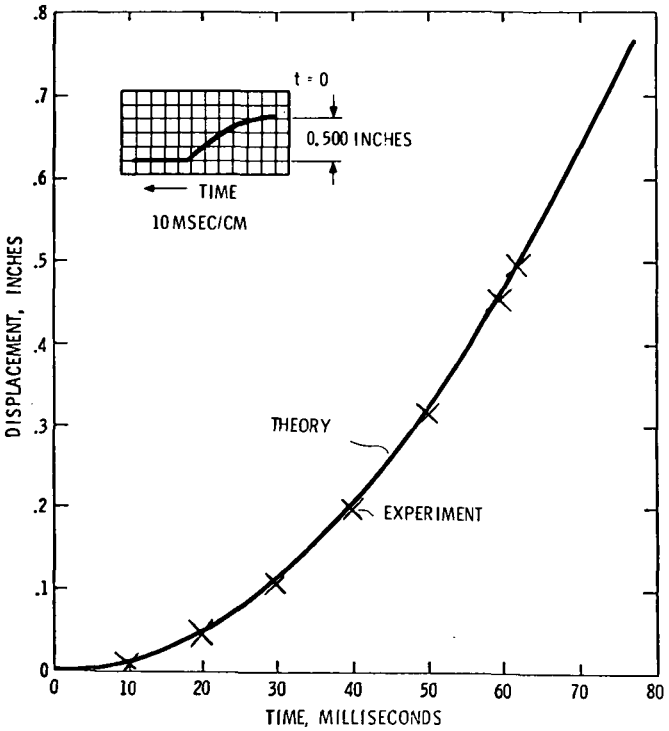

Figure 5. Displacement versus Time for Rolamite with 0.0005 Inch Thick Band

RESULTS

Figure 6 is a graph of the action time required for the roller-cluster with a 0.002 inch thick band to fall 0.500 inch for various values of tension in the band. This graph represents the average of four runs in which the action time was measured at intervals as the band tension was increased or decreased. The error bars show the maximum and minimum values of action time for the four runs at each band tension. It was found that the action time as the band tension was decreased was usually slightly less than the corresponding action time recorded previously when the band tension was being increased. This effect is due to the band "running-in" and friction being reduced. It has been shown that in the tight geometry the band and roller surfaces remate and successive remating will reduce the rolling friction. Thus, the data presented here is for rolamite which has been "run-in" to a fair degree not only by the test procedure but also as it is operated to achieve uniform band tension. Figure 7 is a plot of the average action times for the four band thicknesses used. The data scatter for all of the runs was similar and the error bars were omitted for clarity.

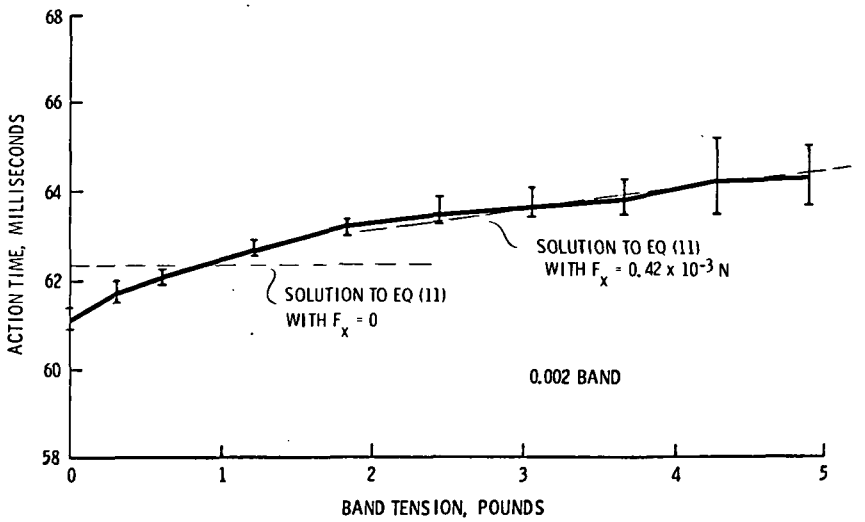

Figure 6. Action Time for 0.5 Inch Roller-Cluster Displacement with 0.002 Inch Band versus Band Tension

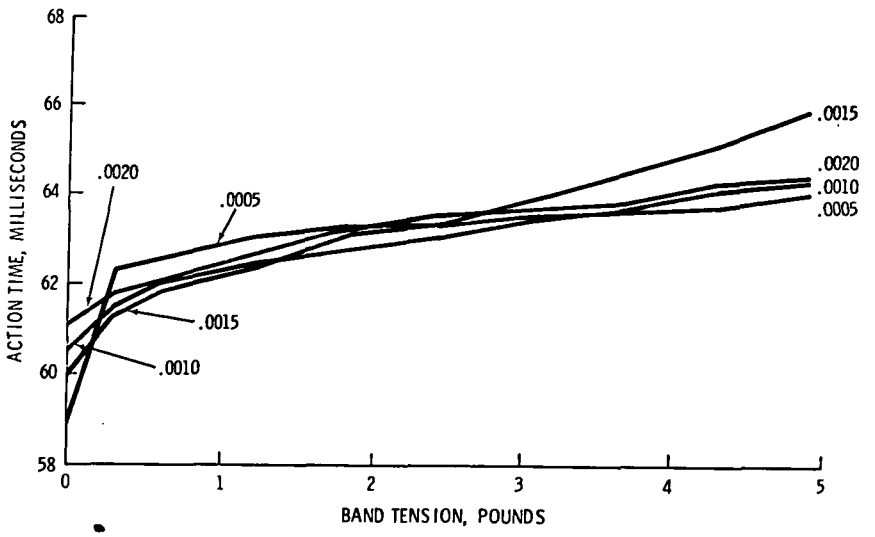

Figure 7. Action Time for 0.5 Inch Roller-Cluster Displacement versus Band Tension for Various Band Thicknesses

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The theoretical action time in the tight-frictionless condition varies slightly with band thickness from 62.18 milliseconds for the 0.0005 inch thick band to 62.37 milliseconds for the 0.002 inch band. At the low band tensions, the experimental action times were less than the theoretical values. The most probable cause of this is slippage between the band and the rollers. At the low tensions, the friction force between the two is low and relative motion is possible. This motion reduces the effective inertia of the rollers and increases the measured acceleration. The thinner bands are pulled to closer contact with the rollers at lower band tension and the effect is reduced. This reasoning is borne out by the relative action time for the various bands at low tensions. The fact that there was slipping between the band and roller at low band tension was demonstrated qualitatively by marking the roller and noting the change in position of the mark after successive operations. Above a band tension of 2.0 pounds for the 0.002 band, there was no slipping. For the 0.0005 band, there was no slipping for band tensions above 0.3 pound.

Calculations based on a geometry and force analysis for the loose rolamite configuration[4] show that at a band tension of 2.5 pounds for the 0.002 inch band there is 0.0003 inch displacement of roller centerline because of loose geometry. However, for the thinner bands, much smaller tensions would be required; for the 0.0005 inch band, only 0.04 pound tension would provide the same tight geometry. But at this very low band tension, the contact pressure between the band and roller would be very small and there would not be sufficient friction between the two to prevent sliding. Thus, the operation of the rolamite depends on the configuration being not only geometrically tight but also kinematically tight as well. Criteria to be satisfied in order that a given rolamite configuration be both geometrically and kinematically tight have not been established. Such criteria are needed for a complete description of the dynamic response.

Figure 8 is a plot of the friction coefficients calculated for the action times shown in Figure 6. It can be seen that, above a critical band tension, the coefficient of friction is

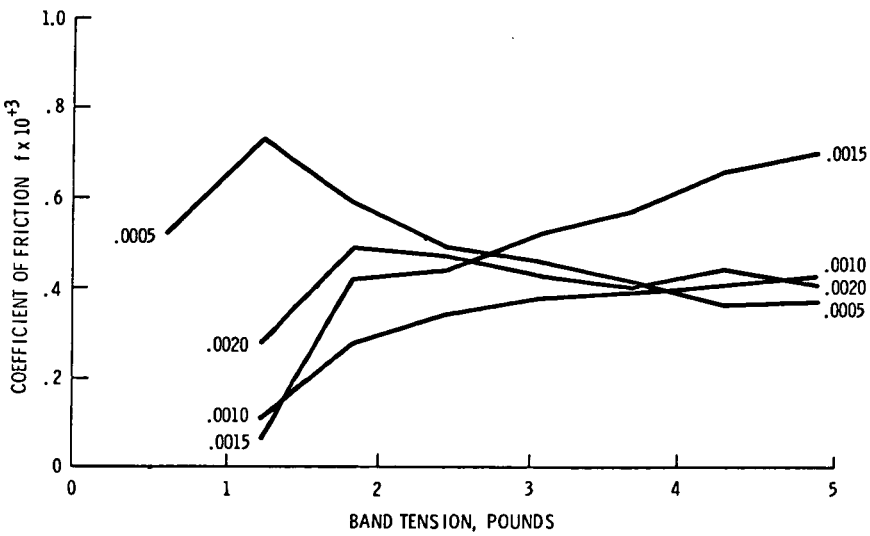

Figure 8. Coefficient of Friction versus Band Tension for Various Band Thicknesses

reasonably constant. This critical band tension is lower for the thin band than it is for the thick bands. The coefficient of friction appears to be reasonably independent of band thickness. The coefficients of friction obtained here are significantly lower than the published values for rolling friction and standard rolling type bearings, particularly at low loads.

It can be concluded that, for values of band tension at which slipping between the band and rollers does not occur and the rolamite configuration may be considered to be tight, the coefficient of friction is relatively independent of both band thickness and band tension. The values for dynamic friction obtained here confirm the results given by Wilkes[5] for quasistatic motion. The procedures developed provide a simple means of measuring the dynamic response of the rolamite mechanism and comparing such response to theoretical predictions.

Results of further investigations to determine the validity of the simple theory, particularly in respect to the effect of band cutouts and the resulting force generation, will be forthcoming.

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1. D. F. Wilkes, Rolamite: A New Mechanical Design Concept, Report SC-RR-67-656A, Sandia Laboratory (1967).

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3. J. N. Shinkle, Sandia Laboratory, and K. G. Hornung, Ohio State University, Private Communication.

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5. D. F. Wilkes, op. cit., p. 44.

N76-19446

MATERIAL PROPERTIES AND TOLERANCES IN ROLAMITE BANDS

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Hamilton Precision Metals

ABSTRACT

The rolamite band, the most important part of the rolamite geometry, is examined for spring force effectiveness and other important properties. Characteristics of typical band alloys Havar and beryllium copper are presented for various production methods. Also presented are data on production of rolamite bands, and some basic guidelines for rolamite band design.

INTRODUCTION

Rolamite is a revolutionary concept in basic mechanics. Its unlimited versatility presents a new dimension in design to mechanical engineers and designers. The basic rolamite consists of rollers, guide rails for the rollers, and a thin metal band.

Hamilton's association with rolamite began in 1966 when thin metal strip of various alloys was supplied to Don Wilkes at Sandia at the time he invented and developed rolamite. During the past year, Hamilton Precision Metals has produced rolamite strip and bands for several companies actively working on applications which utilize rolamite.

Relative Spring Force Effectiveness of Rolamite Bands

The band is the most important part of the rolamite geometry. Therefore, the choice of the band material must be made carefully in order to optimize the design of a rolamite device. Band materials which permit the lowest band thickness to roller diameter ratios, are in general, the types to specify. Usually, these would be materials which display the highest ratios of yield strain to modulus of elasticity.

Using design information from Sandia Laboratories' Research Report[1] on rolamite, the expression y^3/E^2 can be derived. This ratio of the yield strength cubed divided by the modulus of elasticity squared can be defined as the spring force effectiveness of a rolamite band.

Table I shows the relative spring force effectiveness of various metallic band materials compared to BeCu = 100. If the maximum allowable thickness of BeCu 25 around a given size roller will produce a force of 100 units, the maximum allowable thickness of the alternate material around the same roller will produce the amount of force shown.

Important Properties of Metals Used for Rolamite Bands

Because of the unlimited number of ways in which rolamite can be applied, no single metal will ideally satisfy all the requirements for rolamite bands. As in most design considerations, the selection of an alloy for the rolamite band will involve compromises. The metal to be chosen should be the one which will best satisfy the environmental conditions and functional requirements.

Properties of importance in rolamite band applications are yield strength, modulus of elasticity, endurance limit, corrosion resistance, hardness, electrical resistivity, magnetic properties, thermal expansion, and density. These properties and reasons for their consideration are listed in Table II.

TABLE I

Spring Force Ratings for Eight Materials

Material	Condition	Relative Spring Force Effectiveness
Havar	80% CW and Aged	175
Ti (6Al-6V-2 Sn-Fe)	Aged	110
BeCu 25	80% CW and Aged	100
17-7 PH	CH-900	100
18-8 SS	80% CW	60
Elinvar Extra	80% CW and Aged	50
Mylar (Plastic)		40
Phosphor Bronze D	Hard	30

TABLE II

Important Properties of Metals Used for Rolamite Bands

Property	Reason for Consideration
Yield Strength	Sets limit for maximum allowable band thickness with a given roller diameter.
Modulus of Elasticity	Used in determination of amount of force which can be produced when designing cutouts. Also used in determination of band thickness.
Endurance Limit	Used to determine maximum number of allowable flexures at a given stress level
Corrosion Resistance	Must satisfy environmental conditions (pumping device for corrosive liquids).
Magnetic Properties	Bands, rollers, and guide rails must be nonmagnetic in applications where influence on magnetic fields must be avoided. In some cases bands, rollers, and guide rails can serve as flux paths, in which case, selection should be magnetic materials.
Electrical Resistivity	Electrical contacts and switching.
Thermal Expansion	An important consideration for gaging, instrumentation and thermostat applications.
Hardness	Important for applications involving foreign particles and abrasion.
Density	Could be a consideration in a fluidic balance application.

Quantitative data which are useful in selecting the appropriate metal for rolamite bands are compiled in Table III.

TABLE III

Properties of Materials for Rolamite Bands

	Relative Cost	Yield Strength (psi x 10^3)	Modulus of Elasticity (psi x 10^6)	Stress Endurance Limit (psi x 10^3 for 10^8 cycles)	Corrosion Resistance	Electrical Resistivity (μ-Ω-cm)	Thermal Expansion (μ-in/in/°F)	Hardness (R_c)	Relative Spring Force Effectiveness (force units)
Havar (50% CW and Aged)	2.2	265	30	74	Excellent	94	12.5	55	100
Havar (80% CW and Aged)	2.0	320	30	90	Excellent	94	12.5	60	175
BeCu 25 (H)	1.2	110	17	39	Good	6.5	9.3	20	20
BeCu 25 (AT)	1.6	160	19	36	Good	6.5	9.3	39	55
BeCu 25 (80% CW and Aged)	1.5	195	19	45	Good	6.5	9.3	43	100
Ti (6Al-6V-2 Sn-Fe, Aged)	3.8	180	16		Good	157	5.0	48	110
Elvinar Extra (80% CW and Aged)	1.8	200	27.5	60	Very Good	104	3.9	43	50
17-7 PH (Condition CH-900)	1.2	260	29	80	Good	83	9.5	49	100
Phosphor Bronze D (Spring Hard)	1.0	116	16	29	Good	16	10.2	25	30
18-8 S.S. (80% CW)	1.0	210	27.5	80	Good	73	9.9	45	60
Mylar (Plastic)		13	0.5		Excellent	Insulator			40

CHARACTERISTICS OF TYPICAL BAND ALLOYS

Havar

Havar is a nonmagnetic cobalt base alloy which was developed for watch mainspring applications. It is a high-strength alloy particularly suited for applications involving repeated flexing. It is highly resistant to taking a set even when retained in a flexed position for long periods of time. Havar is not hardenable from the solution-annealed condition. In order to harden Havar, it must first be cold worked. Following a cold working process it can be age hardened by heating to a temperature of about 1000°F for one to four hours. When it is desirable to retain the bright metallic lustre, the hardening operation is done in vacuum. If discoloration can be tolerated, Havar can be age hardened in air without adversely affecting its mechanical properties.

Quantitative data specific to rolamite have not yet been developed. It is noted that the endurance limit data in Table III are obtained from the conventional R. R. Moore[2] rotating beam fatigue tests. Test specimens are shown in Figure 1.

Until quantitative rolamite data are developed, performance of Havar in other flat spring applications can serve as a guide in material selection for rolamite bands. Although some spring steels have a higher stress endurance limit than Havar, it is observed that it was not until the development of the high strength cobalt base alloys that unbreakable mainsprings became available. Because the flexing action of a rolamite band resembles the stressing of a watch mainspring, it is likely that Havar will prove to be the alloy best suited for applications involving millions of cycles at high stress levels. The high corrosion resistance of Havar is a useful characteristic in resisting stress corrosion, since even in the static condition, the rolamite band is under stress where it conforms to the rollers.

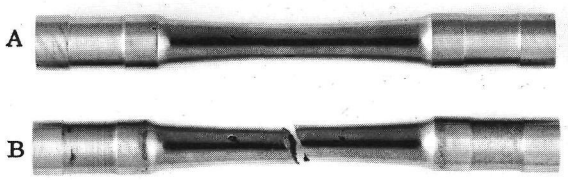

Figure 1A. Test Specimen for R. R. Moore Rotating Beam Fatigue Test
1B. Specimen After Testing to Failure at Stress Level Above the Endurance Limit

The excellent performance of Havar in spring type applications can be attributed to the fact that it is age-hardenable from the cold rolled condition. The microstructure consists of flattened elongated grains resembling laminated platelets. In contrast, the hardened structure of conventional steels has a fine granular texture.

In the solution annealed condition, Havar has an equiaxed grain structure as seen in Figure 2.

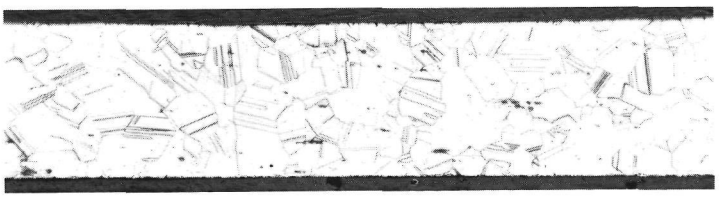

Figure 2. Equiaxed Grain Structure of Solution Annealed Havar (Magn = 100x.)

Cold rolling raises the strength of Havar and produces a laminated texture as seen in Figure 3. Subjecting cold rolled Havar to an age hardening heat treatment further increases the strength without changing the laminated texture. The microstructure of Havar in the age-hardened condition after rolling is seen in Figure 4.

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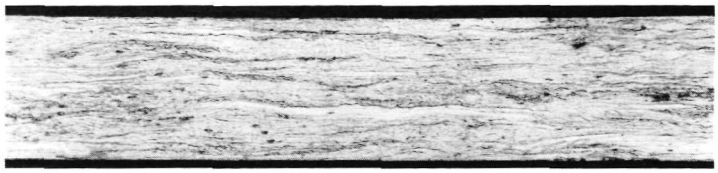

Figure 3. Laminated Grain Texture After 80% Cold Rolling (Magn = 100x.)

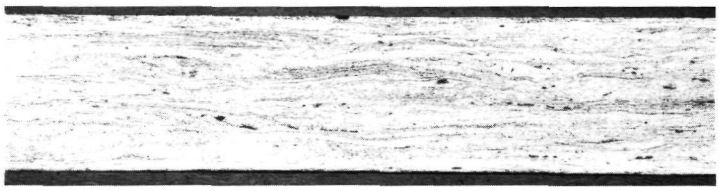

Figure 4. Microstructure of Havar, Cold Rolled 80% and Age Hardened 1 hr. at 1000°F. (Laminated texture remains after age hardening. Magn = 100x.)

Havar Tensile Strength, Yield Strength, and Hardness -- The high strength of Havar is obtained by cold working followed by age hardening. The graph in Figure 5 illustrates tensile and yield strength as a function of cold reduction and heat treatment. The hardness as a function of cold work and heat treatment is illustrated in Figure 6.

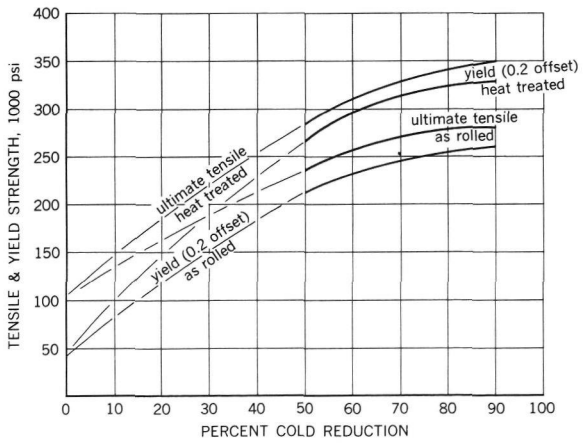

Figure 5. Effect of % Cold Reduction on Strength Properties of .005 Havar Strip "as rolled" and "heat treated at 1000°F"

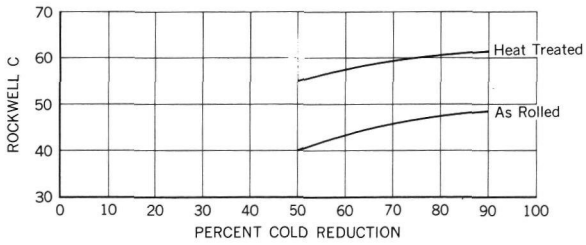

Figure 6. Effect of % Cold Reduction on Hardness of .005 Strip "as rolled" and "heat treated at 1000°F"

Havar Advantages -- The particular advantages of Havar are: (1) high yield strength (above 300,000 psi); (2) high endurance limit (90,000 psi); (3) high modulus of elasticity (30,000,000 psi); (4) high hardness (R_C 60); (5) high corrosion resistance.

Beryllium Copper

BeCu is utilized in many applications requiring spring properties. It can be age hardened from either the annealed condition or from the cold worked condition. A widely used hardening treatment for BeCu is 625°F for two hours in a protective atmosphere. Other time-temperature treatments can be used to change the yield-elongation properties. The proper choice of time-temperature is the one which produces the best functional properties for the application. Tensile, yield, and elongation data as a function of heat treating temperature are shown on Figure 7. Microstructures of BeCu are shown in Figures 8, 9, and 10.

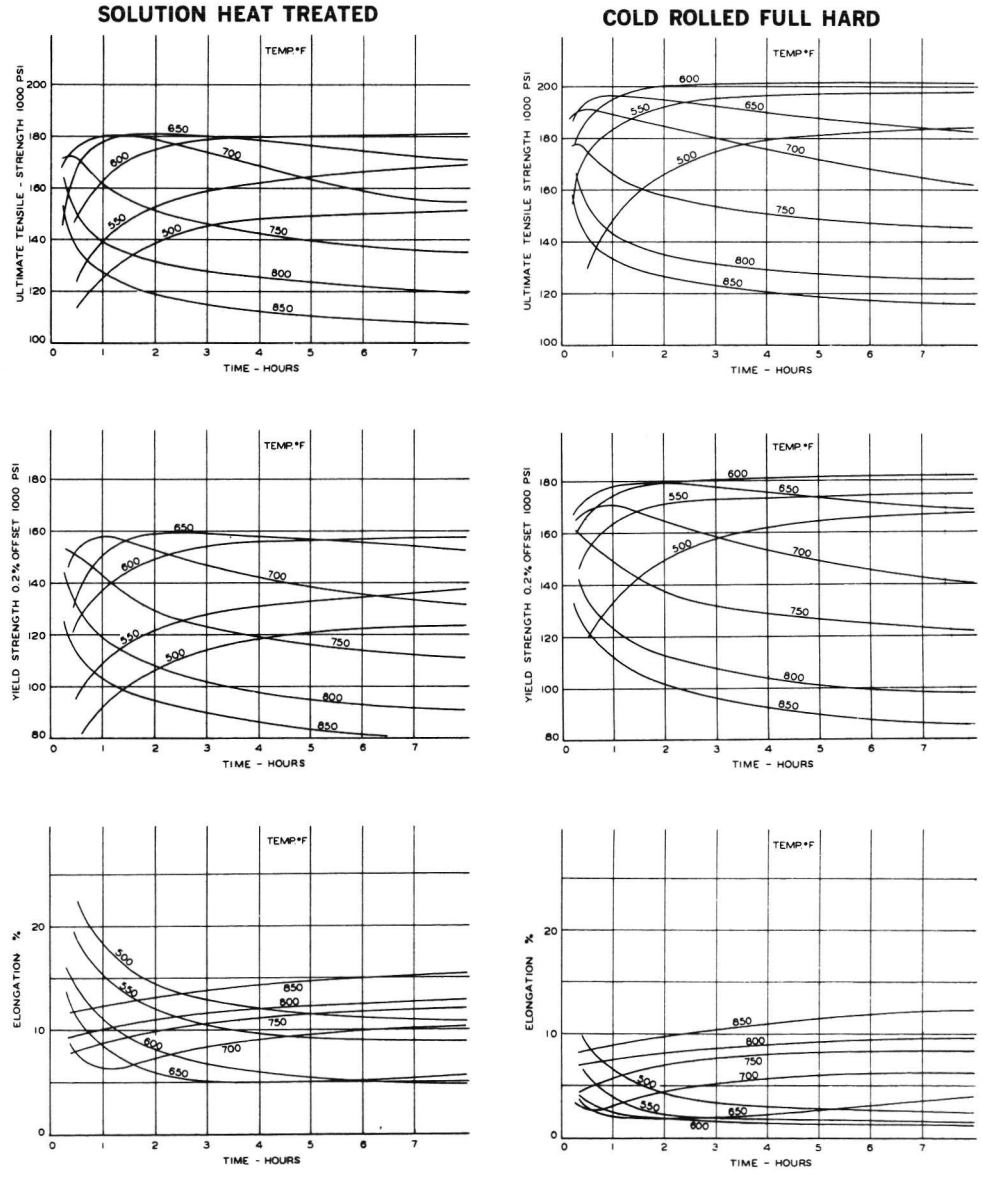

Figure 7. Berylco 25 Alloy, Influence of Age Hardening Time and Temperature on Yield Strength, Tensile Strength and Elongation (Graphs reprinted from Berylco Heat Treatment Bulletin No. 1030-B.)

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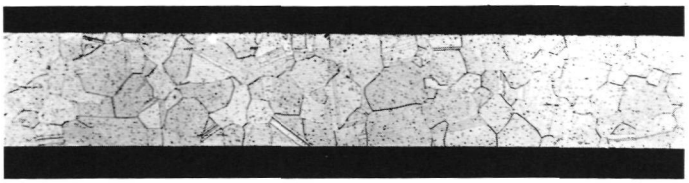

Figure 8. Equiaxed Structure of Annealed BeCu (Magn = 100x.)

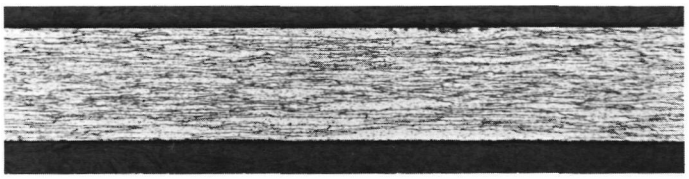

Figure 9. Laminated Texture of BeCu After 80% Cold Rolling (Magn = 100x.)

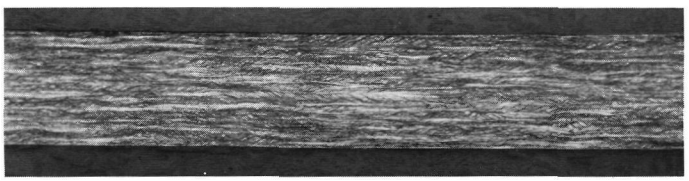

Figure 10. Microstructure of BeCu After 80% Cold Reduction and Age Hardening 1 hr. at 650°F. (Laminated texture remains after age hardening. Magn = 100x.)

Heat Treatment of Some Alloys

The information on heat treatment can be useful in selecting a metal for use at elevated temperatures. BeCu would not be a good choice for operation as a rolamite band if the operating temperature were 500°F or above.

In addition to oxidation, the alloy would continue to age harden and eventually over age. On the other hand, Havar would probably be suitable for use up to 800°F. Recommended heat treating procedures for the seven metals listed in Table III are tabulated in Table IV.

Elevated temperature properties for Havar and several other alloys are shown in Figure 11.

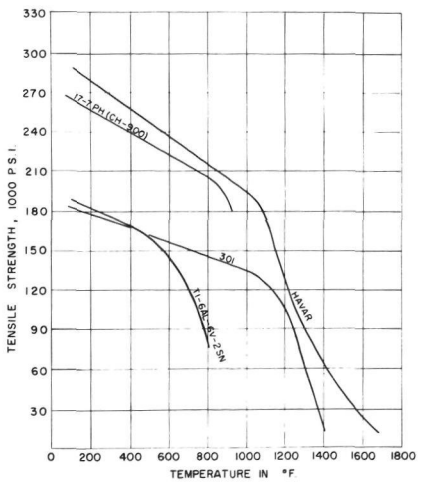

Figure 11. Effect of Temperature on Tensile Strength

Size Availability and Production Tolerances for Rolled Strip

The degree of uniformity of a rolamite system will depend in part on the control of

TABLE IV

Heat Treating Procedures

Havar	Solution treat at 2200°F, water quench. Cold work and age harden at 1000°F for 1 to 4 hours in vacuum. Havar cannot be age hardened from solution treated condition.
BeCu 25	Solution treat at 1500°F, water quench. Age harden from either solution treated or solution treated and cold worked condition. Age harden at 625°F for 2 hours.
17-7 PH (CH 900)	Solution treat at 1950°F. Cold work 60%. Age harden at 900°F for 1 hour.
Elinvar Extra	Solution treat at 1850°F, cool rapidly. Cold work. Age harden at 1250°F for 1 to 4 hours.
18-8 SS	Some improvement in strength properties is obtained by heating cold worked alloy to 900°F for 1 hour.
Phosphor Bronze D	Not hardenable by heat treatment.
Ti (6 Al-6V-2 Sn-1 Fe)	Solution treat at 1650°F for 1 hour and water quench. Age harden at 900-1100°F for 4 to 8 hours.

the dimensions of the strip used to make the band. The rolling tolerances for strip thicknesses ranging from 70 millionths to 0.065 inch are tabulated in Table V. The maximum width of strip is determined by the mill on which the strip is rolled. The minimum width is related to the material thickness and is determined by the capability of the slitting operation. Strip widths for various thicknesses are listed in Table VI. Tolerances on width control are shown in Table VII.

TABLE V

Sizes and Tolerances

Thickness (inches)	Width (inches)	Thickness Tolerances
0.00007 to 0.0004	4 max.	±5%
0.0004 to 0.001	12 max.	±5%
0.0010 to 0.010	12 max.	±0.0001 inch
0.010 to 0.025	12 max.	±0.0002 inch
0.025 to 0.040	12 max.	±0.0003 inch
0.040 to 0.065	12 max.	±0.0005 inch

The width and tolerances may vary depending on properties of alloys being rolled.

TABLE VI

Strip Thickness and Width

Thickness Range (inches)	Width Range (inches)
0.0004 to 0.0008	0.029 min. -14 max.
0.0008 to 0.010	0.029 min. -18 max.
0.010 to 0.020	0.040 min. -18 max.
0.020 to 0.040	0.050 min. -18 max.
0.040 to 0.060	0.080 min. -18 max.
0.060 to 0.080	0.100 min. -18 max.

TABLE VII

Strip Width Tolerances

Thickness (inches)	Under 0.060 Inch Wide (inches)	0.060 to 0.500 Inch Wide (inches)	Over 0.500 Inch Wide (inches)
0.0004-0.005	±0.001	±0.002	±0.005
0.005-0.010	±0.001	±0.003	±0.005
0.010-0.040	±0.002	±0.005	±0.005
0.040-0.080	-	±0.005	±0.005

PRODUCING ROLAMITE BANDS

Photoforming

Photoforming is a process for producing flat, precision parts from thin metals by a combination of photographic and chemical techniques. It affords freedom and flexibility in designing parts and is particularly useful for production of rolamite bands. A variety of burr-free bands produced by photoforming are shown in Figure 12. Some bands have reduced thickness at specific locations to produce desired force effects. Others show cutouts readily obtained by this process. Bands can be photoformed from the metals shown in Table VIII with the tolerances for the various thicknesses as indicated.

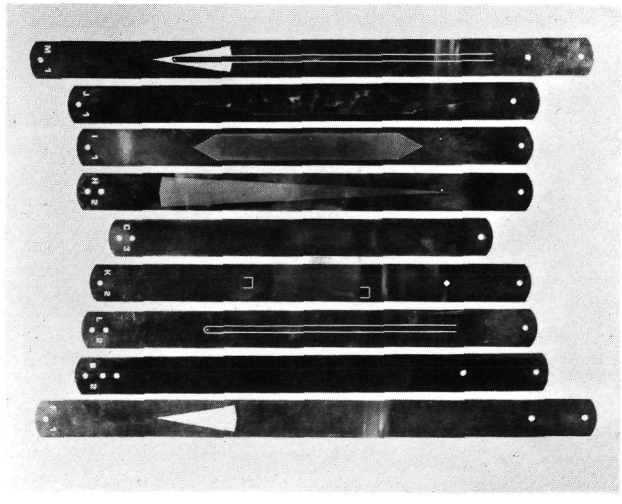

Figure 12. Rolamite Bands

TABLE VIII

Tolerances for Selected Metals at Various Thicknesses

Metals	Thickness (inches)	Tolerance (inches)
Copper and Copper Alloys	0. 001 and below	±0. 0002
	0. 002	±0. 0002
	0. 004	±0. 0002
	0. 005	±0. 0002
	0. 010	±0. 0005
	0. 020	±0. 0020
Havar	0. 001 and below	±0. 0005
	0. 002	±0. 0005
	0. 004	±0. 0005
	0. 005	±0. 0010
Kovar, Carbon Steels, Nickel Silver, Stainless Steels (300 and 400 Series)	0. 001 and below	±0. 0004
	0. 002	±0. 0004
	0. 004	±0. 0005
	0. 005	±0. 0008
	0. 010	±0. 0010
	0. 020	±0. 0020
Titanium	0. 001 and below	±0. 0005
	0. 002	±0. 0010
	0. 004	±0. 0015

Stress Concentrations[1]

"Features in the band such as cutouts or tapers can impair the strength of the band in two ways. First, they reduce the load carrying areas of the band which produce regions of high stress. Second, these features can introduce stress concentrations which further reduce both the allowable working stress and the fatigure life. These considerations must be taken into account when designing a band with cutouts and tapers."

Photoforming capabilities for a typical rolamite band are shown in Figure 13.

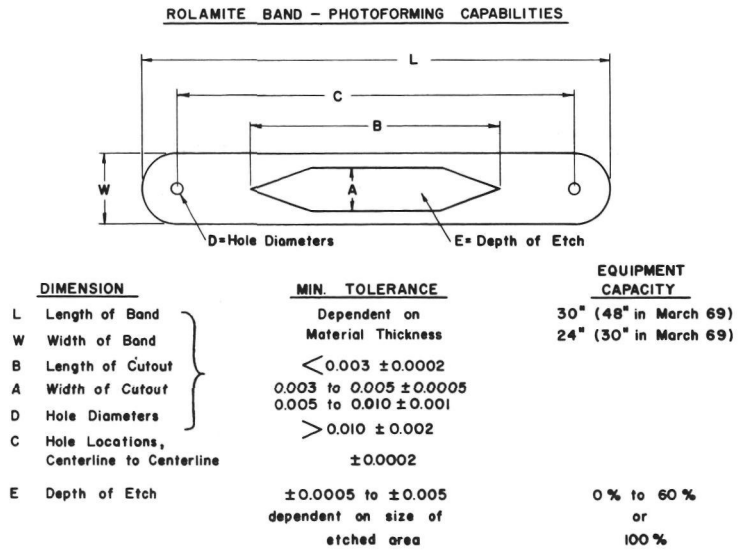

Figure 13. Rolamite Band - Photoforming Capabilities

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ROLAMITE BAND DESIGN FORMULAE

Calculating Band Thickness

Shown in Figure 14 is a portion of a typical rolamite assembly consisting of a single roller of diameter d and an encircling band of thickness t; the band thickness is exaggerated for clarity. The band tension, T, forces the flexible band to conform to the diameter of the roller. This flexing requires that the inner fibers of the band be compressed and the outer fibers be expanded. At some central position, known as the neutral axis, the fibers retain their original length. The actual location of this neutral axis depends on the overall stress situation including the effects of the band tension. However, the stress due to band tension is typically less than 1 percent of the maximum stress due to flexing around the roller. Therefore, to a close approximation the neutral axis is located at the center of the band thickness. The total length of the neutral axis is:

$$l_n = \left(\frac{d}{2} + \frac{t}{2}\right)\theta \qquad (1)$$

where:

l_n = length of neutral axis, inches

d = roller diameter, inches

t = band thickness, inches

θ = wrap angle, radians

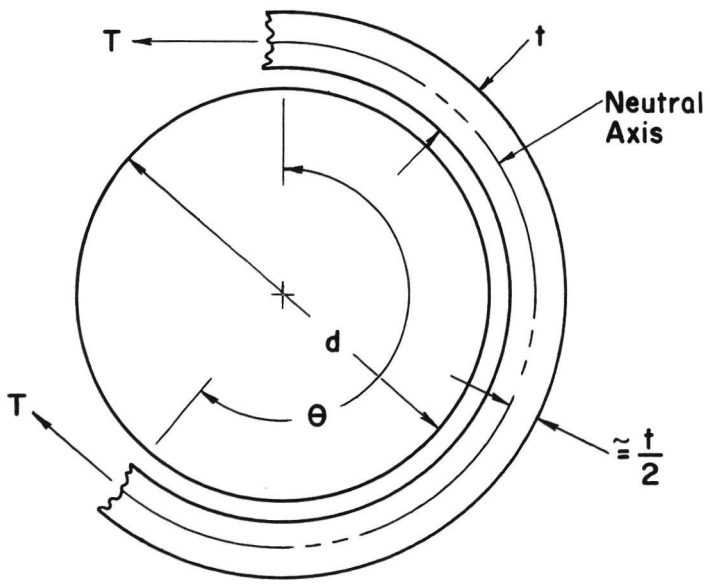

Figure 14. Free Body Diagram of Roller and Band

Similarly, the length of the outer surface is:

$$l_o = \left(\frac{d}{2} + t\right)\theta \tag{2}$$

Strain (ϵ) is defined as the change in length divided by the original length, and since maximum strain occurs on the outer surface:

$$\epsilon_{max} = \frac{l_o - l_n}{l_n} \tag{3}$$

Substituting Equations 1 and 2 for l_n and l_o in Equation 3,

$$\epsilon_{max} = \frac{t}{d + t} \tag{4}$$

From Hooke's Law for elastic behavior, stress (σ) is equal to the product of strain (ϵ) times Young's modulus.

$$\frac{\sigma}{\epsilon} = E \qquad\qquad \sigma = \epsilon E \tag{5}$$

Assuming that the allowable stress is restricted to the yield stress of the band material, substitution of Equation 4 yields an expression for the maximum band thickness:

$$t_{max} = \frac{\sigma_y d}{(E - \sigma_y)} \tag{6}$$

For most engineering materials, the yield stress is much smaller than the modulus of elasticity and to a close approximation:

$$t_{max} \approx \frac{\sigma_y d}{E} \tag{7}$$

and for a roller diameter of one inch

$$t_{max} \approx \frac{\sigma_y}{E} \tag{8}$$

This analysis has assumed that the band was initially flat. (Precurved bands would alter the location of the neutral axis.) Also it should be noted that the fatigue life was not taken into account; this consideration would reduce the value of allowable thickness. If band thickness is to be maximized for a given roller diameter, the band material should be selected to provide a large ratio of yield stress to modulus of elasticity.

The materials which best meet this criterion include the metals commonly used in springs and several of the plastics. The plastics, although allowing larger thicknesses, do have the disadvantages of low strength, plastic "creep," undesirable aging characteristics, and poor stability under changing temperatures.

MATERIAL PROPERTIES AND TOLERANCES IN ROLAMITE BANDS

Band Force Generation

One of the most valuable aspects of the rolamite geometry is the ability to produce forces by band contouring. To a close approximation, the force provided by band contouring within an assembly having equal-sized rollers is:

$$F = \frac{Et^3 (b - a)}{6d^2} \tag{9}$$

where:

F = generated force, pounds

(b - a) = cutout width (difference in local band width at upper and lower roller - guide contact points, inches)

From this equation it is seen that the generated force depends upon the cube of the thickness. Thus, accurate force generation requires that the thickness be controlled very carefully. This includes edge effects such as slitting burrs and crown. Maximum band thickness is very important in the determination of maximum forces available. Substitution of Equation 7 into Equation 9 results in:

$$F_{max} = \frac{\sigma_y^3 \, d(b - a)}{6 E^2} \tag{10}$$

Accordingly, the maximum force available is directly proportional to the cube of the yield strength and inversely proportional to the square of the modulus of elasticity. This ratio can be defined as the "material effectiveness":

$$\text{Material Effectiveness} = \frac{\sigma_y^3}{E^2} \tag{11}$$

As an example, Berylco 25, when in a hard and aged condition, exhibits a material effectiveness of approximately 20. Since this is a commonly used material within rolamite design, it might be considered as a "reference" and we can define "relative material effectiveness" as follows:

$$\text{Relative Material Effectiveness} = \frac{\text{Other Material Effectiveness} \times 100}{\text{Material Effectiveness of Berylco 25}}$$

An interpretation of relative material effectiveness is as follows: "If it can be assumed that for a given band cutout and roller diameter, the maximum allowable thickness of beryllium copper 25 produces a force of 100 grams, the maximum allowable thickness of the alternate material under the same conditions will produce a force in grams equal to the relative material effectiveness." Once again, it is found that the metals commonly used as spring materials are most effective. The final choice of course would be dependent upon cost, ease of fabrication, and other desired properties.

It is interesting to note that among the commonly available plastics only Mylar has a relative material effectiveness of significant value. Mylar is useful as a band material in prototype models. Since it is easily contoured with any sharp cutting instrument, a prototype band can be quickly generated. On the other hand, the aforementioned disadvantages of any plastic material are present.

REFERENCES

1. Wilkes, D. F., Rolamite: A New Mechanical Design Concept, SC-RR-67-656A, December 1967.

2. Moore, H. F., Fatigue Tests, ASM Handbook, 1948 Edition, pp. 118-124.

SESSION I

N76-19447

ROLAMITE DESIGN USING FIGURES OF MERIT

Dr. Lon E. Bell, President, Technar Incorporated

ABSTRACT

Band material properties are discussed in terms of two figures of merit that allow materials to be ranked by their performance. One ranks materials of equal thickness by ability to wrap around small diameter rollers. The second ranks materials by the maximum force generated for a specified roller size. Results are tabulated for a wide range of materials. The figures of merit are used to compute minimum and maximum sizes for certain classes of rolamites.

INTRODUCTION

A rolamite has three basic parts: rollers, band, and guide surfaces. Of these, the band is the most critical. It must flex back and forth at least once during each operation of the rolamite; it may have cutouts for force generation, and it may be under high tension as in a locked geometry. On the other hand, the rollers and guide surfaces are massive and only lightly loaded. This suggests that rolamite design is closely tied to band properties, and the performance of rolamites depends heavily on the particular band material chosen.

Figures of merit that rank materials by their performance as band materials will be presented. The measures are analogous to the strength-to-weight ratio in aeronautical engineering or the stiffness ratio in structural engineering. The engineer can use the rolamite figures of merit and other factors, such as relative cost and environmental conditions, to select the best band material for his particular application.

ROLAMITE FIGURES OF MERIT

Two figures of merit are critical to rolamite design. The first, called the flexivity, F_1, is the maximum band thickness that can be bent around a particular roller size. The importance of flexivity is not apparent from this definition alone. Thicker bands are more easily handled, easier to produce, and generally cost less. Also, if two bands of the same thickness are compared, the one with the better flexivity can be used with smaller rollers, making the overall rolamite smaller. The second figure of merit, called the force factor, F_2, ranks materials according to their force-generating capabilities. For a particular roller size it is a measure of the force that can be produced with band cutouts.

The flexivity and force factors are defined in terms of strength and elastic modulus. As a rolamite operates, the band is flexed back and forth (Figure 1). The strength (or stress) to be used in calculating the figures of merit is related to the material's ability to withstand this type of motion. Data that give the flexures-to-failure at various stress levels are available for most materials (Figure 2). Typically, a definite stress exists, called the endurance stress, below which the material can be flexed an infinite number of times without failing. This value is used for the strength in the flexivity and force factors for rolamites that must operate millions of cycles.

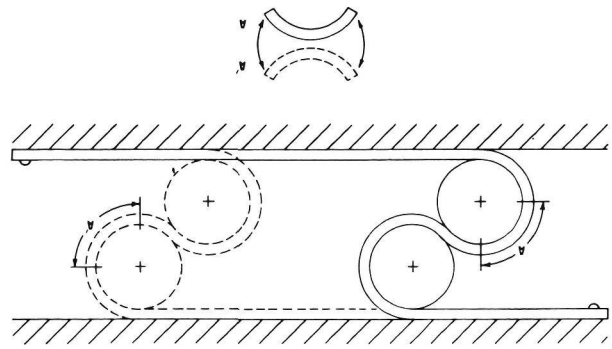

Figure 1. Band Flexure During Rolamite Operation

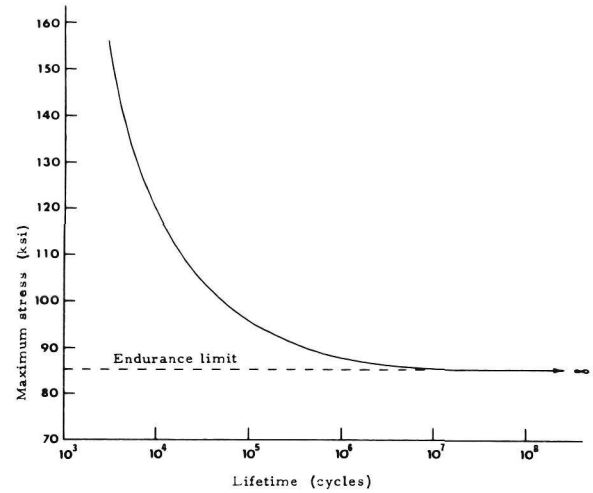

Figure 2. Flexural Fatigue Strength of Titanium Alloy (Ti-6Al-4V)

For a very small number of operations, a different material limitation becomes important. The band may withstand flexing at very high stress levels, but it may permanently deform. As a result, the band would offer a great deal of resistance to roller cluster motion. The best measure of the onset of permanent deformation is the 0.02 percent offset yield stress (that is, the stress at which a material permanently deforms by 0.02 percent). However, it is rarely tabulated, so the more common 0.2 percent yield stress must be used. Experience has shown that rolamites with bands operating at the 0.2 percent yield stress are noticeably affected by the permanent band deformation, and the 0.2 percent yield stress must be considered an upper limit and not a stress level for general operation.

With these definitions of stress, the flexivity and force factor can be defined in terms of material properties and quantities related to the rolamite geometry:

$$F_1 = \sigma/E = t_m/d, \tag{1}$$

$$F_2 = \sigma^3/E^2 = 6F_m/d\Delta w, \tag{2}$$

where:

F_1 = flexivity

F_2 = force factor

σ = stress (endurance or 0.02% or 0.2% yield)

E = elastic modulus

t_m = maximum band thickness

d = roller diameter

F_m = maximum force that can be generated by band cutouts

Δw = difference in cutout width at ends of band's contact with rollers

Again, either the endurance or yield stress can be used in the formulas. The choice depends on whether endurance or limited operations are of interest. To denote the corresponding values of F_1 and F_2, the following notation is used:

F_{1e} = endurance flexivity,

F_{2e} = endurance force factor,

and

F_{1s} = single operation flexivity,

F_{2s} = single operation force factor.

The choice of which figure of merit to use in designing rolamites depends on whether size or force generation is the more important. In any event, the larger the figure of merit, the better the material for that application.

FIGURES OF MERIT VALUES

Values are given in Tables I and II for two classes of materials: the first class, and for general purposes the most important, is corrosion-resistant metals. The second class is metals that rust or readily corrode in other ways, and nonmetallic materials. Also presented are relative cost data for moderate quantities of the materials, maximum service temperature, electrical conductivity, and other pertinent characteristics.

Several materials--titanium alloys, a stainless steel alloy, cobalt-based alloys, beryllium copper, spring steels, two maraging steels, rubbers, and plastics--have the highest flexivities. A titanium alloy, a spring steel, cobalt-based alloys, and two maraging steels have the highest force factors. The choice of the best material for a particular application is a balance of the value of the appropriate figure of merit with other factors such as cost, operating temperatures, corrosive nature of the environment, fabricating ease, and cycles of operation.

TABLE I

Flexivities and Force Factors for Corrosion-Resistant Alloys[1]

Alloy	F_{1s} $\times 10^{+3}$	F_{1e} $\times 10^{+3}$	F_{2s} (psi)	F_{2e} (psi)	Yield Strength $\times 10^{-3}$ (psi)	Endurance Strength $\times 10^{-3}$ (psi)	Elastic Modulus $\times 10^{-6}$ (psi)	Maximum Service Temperature	Cost Index[2]	Electrical Conductivity (% IACS)	Notes
Titanium											
Beta	11.0	4.8	20.3	1.75	170	75	15.5	450°F	6	1.1	Not available in thinner gages
6-6-2	10.9	4.7	20.8	1.64	175	75	16	750	6	1.2	
6-4	10.3	5.4	29.0	2.66	170	90	16.5	750	6	0.9	
Stainless Steel											
Sandvik 11R51	11.7 (10.5)[3]	3.3	46.2 (34.4)	1.05	335 (300)	95	28.5	800	1.5	2.0	Relatively inexpensive; good overall properties
17-7 Ph	9.0	2.8	20.8	0.64	260	80	29	650	0.8	2.1	
AM-350 CRT	8.8	2.4	19.6	0.41	255	70	29	550	1	2.5	
Nickel											
Inconel 718	8.8	3.0	20.0	0.83	260	90	29.5	1300	3	1.4	High temperature alloys
Inconel X750	8.1	1.9	16.1	0.22	250	60	31	1350	2	1.4	
Berylco Nickel 440	7.9	3.3	14.4	1.02	230	95	29	700	2	7.0	Good life with cutouts
Rene 41	7.6	2.0	13.8	0.25	240	63	31.5	1400	4	na	High temperature
Cobalt											
Elgiloy	11.2 (9.5)	3.0	41.2 (25.0)	0.83	330 (280)	90	29.5	900	5	0.6	Very inert; uniform qualities
Havar	11.2 (9.5)	3.0	41.2 (25.0)	0.83	330 (280)	90	29.5	900	5	2.7	
Other											
Paliney 8	10.6	-	19.1	-	170	na	16	na	180	6.7	Platinum alloy; very inert at high temperatures
Beryllium Copper	10.3	3.2	19.9	0.63	190	60	18.5	350°F	1	22	Relatively inexpensive
Ni-Span-C 902	6.8	2.0	7.8	0.20	170	50	25	200	1.5	1.7	Force factor does not change with temperature
Elinvar Extra	6.5	-	7.7	-	180	na	27.5	200	4	na	

(1) Data taken from manufacturer's material property sheets, and "Flat Spring Materials," Product Engineering, March 1, 1965.

(2) Ratio of cost to cost of spring steel.

(3) Values in parentheses at 0.02% offset.

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Lon E. Bell

TABLE II

Flexivities and Force Factors for General Materials[1]

Material	F_{1s} $\times 10^{+3}$	F_{1e} $\times 10^{+3}$	F_{2s} (psi)	F_{2e} (psi)	Yield Strength $\times 10^{-3}$ (psi)	Endurance Strength $\times 10^{-3}$ (psi)	Elastic Modulus $\times 10^{-6}$ (psi)	Maximum Service Temperature (°F)	Cost Index[2]	Electrical Conductivity (% IACS)	Notes
Spring Steels											
SAE 1095	9.7	3.9	28.1	1.79	300	120	31	400	1	na	Rust at 60% relative humidity
SAE 1074	9.7	3.9	28.1	1.79	300	120	31	400	1	na	
Maraging Steels											
350	13.1	4.6	61.2	2.7	355	125	27.0	900	0.8	na	Not available in very thin gages
300	11.3 (9.4)[3]	4.5	39.4 (23.1)	2.5	310 (260)	125	27.5	900	0.6	na	
250	10.7 (8.3)	4.3	33.3 (15.2)	2.1	290 (225)	115	27.0	900	0.5	na	
Medium Alloy Steel											
Vascojet 1000	7.1	4.3	10.9	2.4	215	130	30.4	1000	0.5	na	Not available in very thin gages
Plastics											
Vinylidene chloride-vinyl chloride	125	-	156	-	10[4]	na	0.08	160	0.1	0	Force factors much lower than those given; materials take a permanent set
Polypropylene	78	-	110	-	18	na	0.23	220	0.1	0	
Polyimide	31	-	13	-	14	na	0.45	150	0.4	0	
Polyester	28	-	19	-	23	na	0.80	300	0.6	0	
Rubbers											
Neoprene	5300	-	2.8×10^5	-	3.7	na	0.0007	400	0.4	0	Potentially very high force factors
Natural	5600	-	4.2×10^5	-	3.9	na	0.0006	200	0.4	0	

(1) Data taken from manufacturer's material property sheets.

(2) Ratio of cost to cost of spring steel.

(3) Values in parentheses at 0.02% offset.

(4) 5 percent offset.

PERFORMANCE LIMITS OF ROLAMITES

The figures of merit can be used to determine the size and operating capabilities of rolamite devices. As an example, a minimum size of a rolamite can be estimated. If the band choice is restricted to the corrosion-resistant materials of Table I and the band is assumed to be 0.0001 in. thick (a practical minimum), Equation 1 is used to compute the corresponding roller sizes for endurance and limited operation. Then, from Figure 1, the minimum rolamite size can be estimated. Results are summarized in Table III.

TABLE III

Size Limits for Rolamites

	Minimum Size		Maximum Size	
Parameter	Single Operation	Endurance	Single Operation	Endurance
Figure of merit	$F_{1s} = 10.5$	$F_{1e} = 3.3$	$F_{2s} = 34.4$	$F_{2e} = 2.66$
Band thickness (in.)	0.0001	0.0001	0.037	0.0015
Roller size (in.)	0.010	0.030	3.6	0.28
Overall height (in.)	0.020	0.060	6	0.45
Length (in.)	0.040	0.120	10	0.7

Table III also gives an upper size limit for rolamites that must withstand moderate vibration or shock and operate at all orientations (in essence, the general industrial environment). The limit is found by requiring the available force (from the force factor in Table I) to be ten times the roller weight. With this condition, the rollers will be relatively insensitive to orientation and modest vibration. The calculations assume that the rollers are solid aluminum and that no auxiliary elements such as springs are used. For hollow rollers, or rollers made of very light materials, the limit increases.

As a final example, the force factor can be used to determine the speed of action (acceleration) achievable for a particular roller diameter. The limit is important for rolamites if a high holding force or a "snap action" is needed. Again, the computations are based on conventional rolamites with solid aluminum rollers and metals from Table I. Results are presented in Figure 3. High accelerations, corresponding to rapid action, are possible with very small rolamites, while larger rolamites have slower action. The curves also show that single operation performance is appreciably better than endurance performance, as was the case with the other limits.

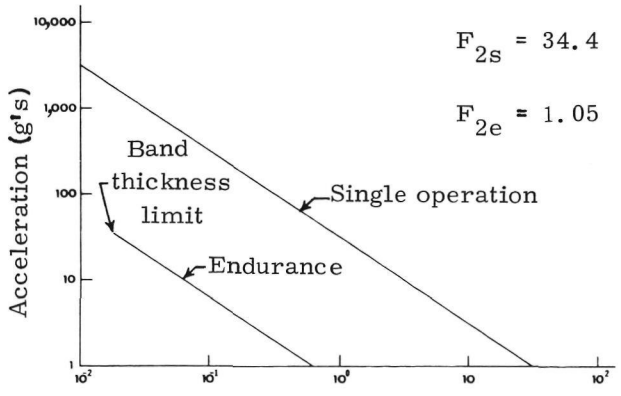

Figure 3. Maximum Roller Cluster Acceleration

ADDRESS TO SYMPOSIUM

Dr. John A. Hornbeck, President
Sandia Laboratories
Albuquerque, New Mexico

OMIT

THE TRANSISTOR AS NEW TECHNOLOGY

Dr. John A. Hornbeck, President

Sandia Laboratories
Albuquerque, New Mexico

Speaking for Sandia and its Office of Industrial Cooperation, I am pleased that we are taking part, along with the University's Technology Application Center, in the sponsorship of this Symposium. I call to your attention that three other companies--Rolamite Technology, Inc., Technar, Inc., and Hamilton Precision Metals Division of the Hamilton Watch Company--are also cooperating actively in this venture. And I am particularly pleased, tonight, again to meet Don Wilkes, the inventor of rolamite.

I am reminded, by this gathering, of the activities in which I participated many years ago, following the invention of the transistor. There are many parallels, and it is my belief that rolamite, like the transistor of that time, is on its way up. Rolamite as a concept is about 2 years old. In fact, I arrived at Sandia just in time for Don to get his good idea. Thus I had opportunities to participate in decisions that influenced the future of rolamite.

One of our more significant decisions was to encourage Sandia's Office of Industrial Cooperation to disseminate information widely on rolamite technology, and this Symposium clearly reflects this policy; it is an organized attempt to teach, and thus to transfer, technology. This "transfer of technology" is the theme of the remarks that I will make here tonight.

Why is Sandia actively interested in the transfer of technology? Chiefly because we as scientists subscribe to the free circulation of information, but also because it is AEC policy to disclose whatever unclassified technical information has been developed at its laboratories. This is a wise policy. Time and again we have seen how the free exchange of information has been a major factor in the technological growth of this country.

I would like to suggest that technological transfer is not a new problem, but, rather, one that has always accompanied civilization. Some years ago I was associated with an organization that had a technological transfer problem, and it has occurred to me that a recounting of the history of how that problem was handled might provide us with some useful guidelines for today. I refer, of course, to the invention of the transistor and how Bell Telephone Laboratories handled this new baby, from the prenatal period until it was weaned and finally went out on its own.

Let's go back to 1948 and the first public announcement. The New York Times, on July 1, carried this item at the end of a column of radio chitchat:

> "A device called the transistor, which has several applications in radio where a vacuum tube ordinarily is employed, was demonstrated for the first time yesterday at Bell Telephone Laboratories, 463 West Street, where it was invented."

The item went on to say that the transistor came in the shape of a metal cylinder, 1/2 inch long; that it contained no vacuum, plate, or grid; and that the sole working parts were two fine wires attached to a semiconductor. This, of course, is what we used to call a point contact transistor.

At the time, very little attention was paid to this announcement, yet this tiny device was the forerunner of a revolution in solid-state technology. Today, a more technically aware press has given broad coverage to rolamite. The climate and importance of technology have changed since the invention of the transistor, and one of our problems today is not to overplay or underplay new technology.

But, to return to the transistor. The time is 1947, the war was over, and Bell Telephone Laboratories was rebuilding. Jim Fisk, Bill Shockley, and some others proceeded to gather an

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extremely talented group of solid-state physicists. (At least four of these people have since received Nobel prizes.) Bill Shockley departed from the conventional path in research by suggesting that his people do fundamental research along directed lines. He proposed they gain an understanding of the basic phenomena of semiconductors. The practical aim at the outset was the development of a semiconductor amplifier.

Here is how the discovery went. Shockley had earlier proposed a "field effect" theory for semiconductors: if you could apply a strong enough electrical field to the surface of a semiconductor, you could alter the resistivity of the entire semiconductor. If you then added electrodes and varied the resistivity, you might get some kind of amplification. The theory sounded good, but experiments did not confirm it. The experimental failures led Walter Brattain and John Bardeen to some fundamental studies of surface effects, and it was in the course of this work that the point contact transistor was invented.

In late 1947, Brattain applied some strange-looking chemical material, commonly called "goo," to the surface of a single crystal of germanium to which some wires and meters were attached. When he applied a voltage to this goo--to cause an electric field at the surface--he found that the current flow in the germanium was affected. He then replaced the goo, first with evaporated gold spots and next with metal contacts closely spaced (cat's whiskers), and saw voltage amplification. On the next day, he spaced the cat's whiskers about 1 mil apart and observed an audio power gain of about 18 times.

His bosses, Drs. Brown and Fletcher, were intrigued and asked, "Will it oscillate?" It did. They knew then that here was something really new and you can imagine their exhilaration. This was tempered with concern, however, for they now were faced with a new set of problems. What about a timely public announcement? What to do about publication? What about patent protection?

Fortunately, BTL had experience with new technology and followed a fairly sensible course. They first resolved to learn the implications of this new device, and called in their own experts in various fields to analyze it and see how it could be used and improved.

The practical problem of providing scarce samples to these people for their analysis was met by setting up a development group that worked closely with the researchers.

Public announcement was deliberately deferred until the Lab's scientists felt they knew technically what they were talking about and could give other scientists enough information to enable them to reproduce the work. Also, patent applications had to be filed to protect the interests of the shareholders. As it turned out, these activities took some 6 months and, in June 1948, the announcement was made.

One week before the public announcement, a disclosure was made to the Military. Somewhat earlier, DOD had wisely concurred in a BTL recommendation that the transistor be unclassified. New information of a fundamental nature just cannot stand being classified: it will not stay that way very long.

The devices that were introduced in that June were themselves commendable, following 6 months of intensive development: their power output was 50 milliwatts, frequency response 10 megacycles, and power gain 20 db or 100 times. Voice frequency and TV video signal amplification were demonstrated, as was a superheterodyne radio containing nothing but semiconductors. And while there had been considerable technological advance in these months, this was accompanied by parallel advances in research. Before the end of '48 Shockley had formulated his theory of the p-n junction transistor which got away from the point contacts and established a solid foundation for semiconductor physics and device theory. I believe Shockley's work made possible the rapid growth of transistor and semiconductor technology, for scientists and engineers now had all the tools needed to design transistors.

After this early work, the field of semiconductors expanded dramatically and, looking back, I conclude that one reason it did was because the transistor was born into a society technically able to exploit this new device. We knew about vacuum tubes and four-pole parameters, transit-time effects, and pulse applications.

Another reason for the rapid advance, and here I may have some partiality, was the policy of BTL relating to the disclosure of transistor information and the granting of nonexclusive licenses to all comers at a reasonable royalty. The BTL information policy here was not passive, but active, and its cornerstore was--and is today--to publish new science and technology at the earliest possible time. Shockley's book, "Electrons and Holes in Semiconductors," which gave the whole semiconductor device theory, came out in 1950 and is a good illustration of this publishing policy. Publishing also forced other laboratories to disclose their work because, among other things, their people wanted credit for work they were doing.

In September 1951, the Bell Laboratories sponsored a 5-day "Symposium on Properties and Applications of Transistors," attended by military personnel and their contractors. Over 400 people were present, and one important product was an 800-page text (the proceedings of the meetings) which dealt in detail with the subject matter.

Next, in April 1952, an 8-day symposium was held for licensees, both foreign and domestic. This symposium produced a two-volume, 840-page book on transistor technology. Incidentally, I might mention that the price of admission for that symposium was $25,000--partly to hold down the attendance. The fee could be taken out of royalties to the Bell System, which meant that the symposium actually resulted in no additional cost to the licensee.

Shortly after that, in June 1952, the Labs' research department held a 6-day symposium for teachers from more than 30 different universities. The object was to encourage the introduction of transistor physics into university courses. One result of this symposium was a paper in the Physical Review, coauthored by 60 authors from 33 different institutions, which described an experimental confirmation of an Einstein equation linking diffusion coefficient to mobility.

The last Bell Labs symposium on transistors was held in June 1956. This time we advocated diffusion as the technology and silicon, rather than germanium, as the material. By then, 12 years and four symposia later, the world had about caught up with Bell Laboratories, and the Labs decided to conclude their teaching efforts in the field of semiconductors.

Consider, now, some of the parallels between the transistor and rolamite. Like the transistor, rolamite grew out of a planned exploratory development program. Our objective was to solve specific electromechanical problems that arose from our business. Don Wilkes was given the assignment and, characteristically, he delivered.

Once invented, the same questions arose about timely disclosure, patent coverage, classification, etc. What did Sandia do? The parallel continues. We first explored the implications of rolamite with people in various fields and tried to gain better understanding of its theory. We sought to obtain broad patent coverage so that it would be possible, under the AEC's policy, to grant nonexclusive, royalty-free licenses to anyone. With the flow of basic information thus unrestricted, it then became possible to have symposia such as this.

In our publishing policy we sought to avoid giving competitive advantage to anyone, including the Bell System. We also sought to teach, actively, and one problem here is how to teach both big and small organizations.

Our Office of Industrial Cooperation is now trying to find ways to convey new technology, particularly to small businesses. It is clear that large organizations with greater resources are better able to absorb new developments than smaller organizations. For this reason, I am particularly pleased to note, here at this symposium, the good representation from small businesses. I hope their experiments are successful.

APPLICATIONS WORKSHOPS

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APPLICATIONS WORKSHOP III-A-1

N76-19448

BEARINGS AND SUSPENSION

E. N. Leslie, Sandia Laboratories, Albuquerque, Chairman
Workshop Consultants: Gordon Wilkes (RTI) and
William Pryor (RTI)

ROTARY-TO-LINEAR CONVERTER

During the session, several rolamite applications were discussed. The first dealt with a rotary-to-linear converter for a pump and was presented by Mr. Mario Di Giovanni, Vice President, Statham Instruments, Inc. The geometrical configuration is illustrated in Figure 1. Torque is applied to one of the rollers, which in turn causes linear motion of the housing which is free to translate. The housing then drives a piston to provide the desired pumping action. The housing is to provide a thrust load of up to 25 pounds and the mechanism is to have a life of about a hundred million cycles. Mr. Di Giovanni's questions were: (1) Does this arrangement violate any rolamite principle? and (2) How can band failures which have occurred on experimental models be prevented?

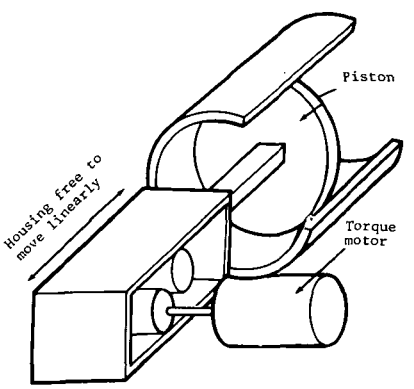

Figure 1. Rotary to Linear Converter

In the discussion that followed, Mr. Di Giovanni's questions were answered essentially as follows. First, the mechanism seems to be a workable configuration and does not violate any rolamite principles of operation. Second, with regard to increasing the life of the band, it was suggested that the band tension be set at a value low enough to place the stress in the band below the endurance limit of the material.

* * *

BAND ATTACHMENT AND TENSION

Mr. Jack Chambers of Statham asked about methods of tensioning the band and of attaching the band to the case. Don Wilkes described some of his techniques which included increasing the thickness of the band at the attachment points and then mechanically attaching the band to the housing. Also, Mr. Wilkes indicated that in his miniature designs he placed thickened tabs on the end of the band. These tabs rested in slots in each end of the housing. To obtain the correct band tension, the band length is carefully designed so that when the band is entwined around the rollers and the tabs are engaged in the slots, the tension is that desired.

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ROTARY BEARINGS

Mr. Ernesto Martin, Communications Satellite Corporation, indicated that his company is interested in applying rolamite to low speed, low level, very long life rotary bearings for space applications. Mr. Martin asked Don Wilkes to comment on his work on rotary bearings. Mr. Wilkes' answer, in summary, was that his work on rotary bearings has been limited. A problem that has never been solved is that in a rotary geometry there is a strong tendency for the band to creep out and chafe against the side of the race. This problem can undoubtedly be overcome if a sufficient development effort is provided.

* * *

FRICTION IN LINEAR BEARINGS

Mr. Norman Czajkowski, Naval Ordnance Laboratory, indicated an interest in linear bearings. He asked for information on the frictional losses in the geometry when the applied force is out of the plane of the roller cluster translational axis. About the only answer to Mr. Czajkowski's question was to refer him to the Sandia Laboratories development report on rolamite, which included sections on side loading and frictional losses in the geometry.

* * *

ROLAMITE GAGE DESIGN

Mr. Charles Hughes, Hughes Engineering Company, described a rolamite gage design which provides an amplified motion of a dial for a very small motion of the rolamite cluster. Figure 2 shows a sketch of the gage.

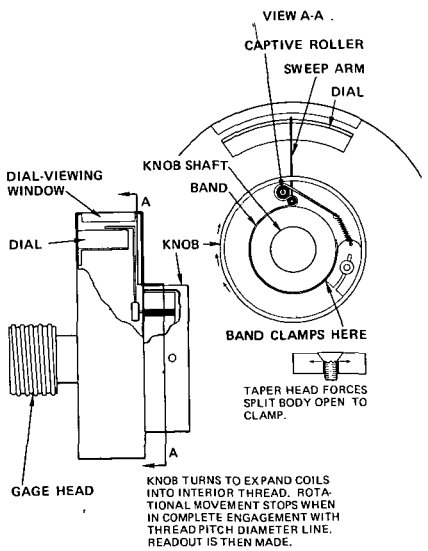

Figure 2. Rolamite Gage

From the description of the device it was not clear where the input to the gage was attached. Mr. Hughes indicated that in his design about 0.002 inch of travel of the roller cluster would provide a dial movement at the readout window of 0.050 inch. The size of gage was not determined.

* * *

ODOMETERS

Mr. David Overman, Harry Diamond Laboratories, indicated that he was interested in the rolamite geometry for use in odometers. He asked for comments on increasing the scale factor of odometers by the use of rolamite. Elmer Leslie, Sandia Laboratories, pointed out that rolamite geometry can provide a higher speed ratio, with only one set of rollers, than can be provided by a single stage of gearing. Second, in an inertial odometer, inertial loads on bearing-mounted mechanisms can cause high and variable frictional losses. However, a rolamite odometer does not require placing bearings in the acceleration field. Some work on odometers performed at Sandia Laboratories showed that a rolamite odometer using only one set of rollers could provide a scale factor of 1 inch of roller travel corresponding to 2.7 miles of vehicle travel.

* * *

ROLAMITE MECHANISM PROPERTIES

Mr. Heinz Runge of National Dairy Products Corporation asked if anyone had used rolamite with timing belts for bands and gears for rollers, etc. His company was interested in using rolamite as a mechanism in high-speed packaging machinery. His interest was mainly concerned with unique motions afforded by rolamite rather than the low friction aspects. It seems that rolamite mechanisms might simplify some of the machinery, thereby reducing costs. No one at the workshop had used rolamite in this manner. Even so, the panel agreed that it was valid to consider rolamite more for its mechanism properties than for its frictional properties.

N76-19449

APPLICATIONS WORKSHOP III-A-2

INSTRUMENTATION

Dean Gladow, Rolamite Technology, Inc., Chairman
Workshop Consultants: Bruce Hodgins (SL)
and Rodney Moseman (Hamilton)

INTRODUCTION

Several inherent features of the rolamite concept look particularly inviting for instruments. The means of amplification, the gravity and inertial balancing techniques, the low friction, generation of selected forces, and the capability of matching inputs and outputs of various shapes and forms are all applicable to various instruments.

Specific interests of participants in the workshop included applications as dial indicators, miniature inertial devices, tape-recorder devices, low pressure transducers, rotary switches, aircraft part instrumentation controls, dimensional gages and industrial timing and control mechanisms.

* * *

SENSING PRESSURE

Discussion began on the general topic of using rolamite to sense pressure, with the general guidelines that 5 percent variations in the band are likely to produce errors which become important at low pressures. Chairman Gladow pointed out, "Assuming that you wish to use the rolamite band as a spring, at low pressures you're probably also considering very small sizes. It should be mentioned that the smaller sizes become increasingly dependent on contaminants in the system and on the properties of the band materials."

* * *

HOLLOW TUBE SENSOR

One way of using rolamite as a pressure transducer is fabrication of the band as a hollow tube. This technique avoids the need for close-fitting side plates, required in the usual rolamite fluid system. Using the cluster as a piston obviously cannot provide a perfect seal because of leakage past the ends of the rollers. On the other hand, a preformed tubular band can provide an excellent seal.

* * *

PRODUCING PISTON-TYPE SENSORS

Sandia has not attempted to obtain perfect sealing in using the roller cluster as a piston, but minimizes the flow past the rollers so that it becomes insignificant as compared to that through a sharp edge orifice. In devices measuring about an inch and a half in length, clearance is down to a half a mil or smaller. With this clearance, the viscous forces become large and the flow is very small; typical flows are 0.0001 cubic inch per second.

Manufacturing the rolamite case has been one of the main problems in trying to minimize clearances, with the best method that of vacuum drawing glass. The technique achieves dimensional accuracies of ±0.0002 inch, but ±0.0004 or ±0.0005 is more typical. In

vacuum drawing, a mandrel of the desired cross section is placed inside a round glass tube. One end of it is sealed off and a vacuum is drawn on the other end. With the application of heat, the glass is drawn onto the material. Since the coefficient of expansion of the mandrel, which is typically stainless steel, is larger, it will shrink away for removal. Because it will seal with Kovar, 7052 glass is used.

In the finished devices a spring-loaded bar is mounted so that when the rollers pass by it, it will spring up. If the glass case breaks, it provides a fail-safe arrangement.

* * *

EFFECT OF WEAR-IN

Rolamite has a tendency to "wear-in." Dean Gladow discussed measurement of wear-in as it affects force generation variations. Most of the information available involves roller sizes of 3/8 and 1/2 inch. For these, force variations are typically about 2 to 3 percent. For example, a band with a rectangular cutout in it should theoretically produce a force deflection curve which is a step function existing for a given distance. However, experimental testing reveals two important deviations: a rounding of the corners, and a jaggedness (or noise). The jaggedness is somewhat reduced with repeated traverses of the roller cluster. Typically, the total friction might be reduced by about 20 percent after 50 traverses. Interestingly, after the repeated traverses, the jagged pattern will still be quite recognizable with the high points still at the same place. This indicates very good rematching with little, if any, slippage of the roller with respect to the band.

* * *

EFFECT OF GUIDE RAILS

In many applications, rolamite requires a guide rail, but there are ways of avoiding them. If the total motion is less than one wetted perimeter of the roller, the band can pin directly to the roller. Secondly, if side loads are small as compared to the normal force produced by the band tension, rails are not necessary.

But rails can be designed so that the additional friction is very low. The analysis of friction due to the side rails has to be done on an energy basis. A point on the end of a roller which is close to the point of contact between the roller and the flat surface has a very small instantaneous velocity. Therefore, if a side rail is to be used, its height should be kept small as compared to the roller diameter so that the area of contact is in the zone of small velocities. If this condition is met, the energy loss and coefficient of friction will be small. A typical rail height 1/30 of the roller diameter will provide quite high side-load carrying capability.

* * *

EFFECT OF BAND SLIPPAGE

Macroslipping or actual visual slippage between the rollers and band depends on band tension. Less is known about preventing or analyzing microslippage, or creep. As Chairman Gladow pointed out, all slippage can be prevented by attaching the band physically to a roller by riveting, pinning, or spot welding--when motion is restricted to less than one wetted perimeter. "If this is not possible or desirable, the possibility of macroslippage can be analyzed to a first approximation by use of the basic bolting formula, $T_1/T_2 = e^{\mu\beta}$, where T_1 is the tension on the tight side, T_2 is the tension on the loose side, μ is the coefficient of friction, and β is the wrap angle. In rolamite, we have a better situation than in normal belting systems because of larger wrap angles. By inspection of the rolamite geometry, it can be seen that the wrap angle has a minimum value of 180 degrees and a maximum value of 270 degrees. Use of this formula will provide a first approximation of the tension required to prevent slippage. To be exact, it would also be necessary to consider the flexural strength of the band which tends to decrease total friction. For a given application, knowledge about expected inertial loads and/or torques which might be applied to the system can be used to determine the difference in tension on the tight and slack sides. Use of the belting formula then allows the calculation of the required initial tension. Work remains to be done on the subject of microslippage."

* * *

MINIMUM BAND WIDTH

Minimum width for rolamite bands is dependent on the overall size of the unit, but the determining factor of band width is usually the requirement of alignment. Obviously, use of a wide band and small diameter rollers leads to a strong tendency for alignment. As discussed, the normally strong alignment tendency in a rolamite is an important factor in low friction characteristics. Therefore, the required frictional behavior as well as any loading which might tend to disturb the alignment must be considered. Narrow band alignment could be provided by interaction of the rollers and guide rails. If this were done, a very narrow band could be used, although the rollers would still have to be of sufficient length for adequate alignment. This method could be particularly effective if each roller surface were provided with a groove which was just deep enough to accept the band. The ends of the rollers would then contact each other as well as the guide surface to provide the alignment.

* * *

WIRE TO REPLACE BAND

The workshop proposed that a band could be made by using two wires. Each would operate in a groove near the end of the roller to provide good alignment. The diameter of the wire would have to be small to avoid yielding; essentially, the diameter could be no larger than the maximum thickness of a band made of the same material.

* * *

ACCURACY OF BAND CUTOUTS

In reply to a question about predicted and actual generated forces, Chairman Gladow explained some of the assumptions of the theoretical analysis. "The simplified formula predicts the force to be:

$$F = \frac{Et^3 (a-b)}{6d^2}.$$

PREDICTIONS

One usual assumption is that Young's modulus, E, is the classical textbook value. More accurately, the "plate modulus" should be used since the band width is typically very large compared to its thickness. The plate modulus is

$$\frac{E}{1 - \nu^2}$$

where ν is Poisson's ratio. Also, the roller diameter, d, should be increased by approximately the thickness of the band, or even more exactly, by twice the distance from the roller surface to the neutral stress plane of the band. The simplified formula also assumes that the band was initially flat and that the cutout is present only at one roller contact point. I refer you to Dr. Cadman's paper for a thorough analysis of rolamite force generations. His generalized equations can be used to determine the effect of band thickness changes, variations in Young's modulus, precurved bands, and cutouts at all inflection points. However, we find that the simplified formula is usually sufficiently accurate and complete enough to do preliminary design. In fact, we can usually build prototype units without referring to the generalized equation."

CALCULATIONS

Sandia makes use of the generalized equation through computer design. Cadman's computer programs for force equations can obtain a complete force profile for a given geometry. At this point, however, one cannot define a force function and have the computer define the design parameters.

* * *

SPECIAL CUTOUTS

Since large cutouts in the band often create problems (for example, with spool rollers), they may be avoided in two ways: One is the method that Hamilton has used, in which the bands are etched only part way through. This method is quite effective since the generated force is proportional to the cube of the thickness. Therefore, if one-half of the material thickness is removed by etching, the remaining thickness has only one-eighth of the original flexural strength. Therefore, the depth of etching usually need not be controlled to any high accuracy. A second method of maintaining band integrity is to produce the desired bank weakening by etching a screen pattern into the band instead of a complete cutout.

* * *

ACCURACY OF PRECURVED BANDS

In approximate performance force generation, precurved bands may often be used, but in general cutouts are recommended to control force generation to a precise level. However, heat treating on a mandrel can provide precurved shapes which have much more controlled behavior than cold-formed bands. Hamilton's experience with preformed shapes other than coil springs indicates that production techniques are available to the state of art required for many preforming applications.

* * *

DAMPING CLUSTER MOTION WITH VISCOUS LAYERS

Damping fits well into the general field of instruments. One method of damping involves including viscous material between a sandwich band. If this method is used, damping is almost independent of roller diameter.

* * *

SHARP ORIFICE DAMPING

Another method of damping uses the cluster as a piston, to force a fluid through an orifice. Bruce Hodgins (SL), explained that Sandia's "pumper units" were based on this principle. A sharp-edged orifice in the band makes timing independent of temperature. The rollers, relatively long but of small diameter to reduce leakage past the ends, are in the cross-bar of a T-shaped case. The vertical leg of the T serves as a return path for the fluid. This unit is also provided with electrical contacts for switching, in an overall size typically 1/2 by 3/4 inch or 1-1/2 by 2 inches. The fluid is a silicon oil very temperature-stable in viscosity.

* * *

EFFECTS OF ACCELERATION

Rolamite assemblies can be balanced against acceleration in both linear and rotary modes, and remain balanced regardless of frequency and/or level. Departures from balance would be second-order effects--for example, with a loose geometry the rollers would have a slight linear motion without any motion relative to the band. Linear is due to the translation of the roller cluster; rotational is due to the rotation of the rollers. The rotational inertia is proportional to the square of the radius of gyration. Therefore, the inertial behavior of a rolamite unit can be changed considerably by changing the radius of gyration (most simply by changing the roller diameter size). On the other hand, a high inertial system with light weight can be constructed using tubular rollers. A low inertia system can be effected by using spool-shaped rollers.

* * *

SENSITIVITY TO LINEAR AND ROTARY ACCELERATION

For a device sensitive to linear acceleration but not to rotary, the rollers should have the same rotational inertia, which is most easily accomplished by making them identical. The unit is completely insensitive to rotary acceleration around the point where the rollers contact. To make a unit sensitive to rotary but not to linear acceleration, counterbalance one roller only and not both.

ROLLER SIZE EFFECTS

Different sized rollers in a rolamite are obviously valuable because of differing speed ratios, but a second advantage is the variation of inertial behavior. A system of much higher rotational inertia results if a large roller is used in conjunction with a small one. A third advantage is that the force being generated is proportional to the square of the diameter. Therefore, the force produced by a given band can be widely varied by using different size rollers.

N76-19450

ELECTROMECHANICAL DEVICES

F. A. Duimstra, Sandia Laboratories, Chairman
Workshop Consultants: R. W. Diller (Technar), Walter Barbier (SL), and Lon E. Bell (Technar)

SANDIA DEVICES

Chairman Duimstra began the discussion by commenting about recent work on rolamite electromechanical devices at Sandia. Sandia is working actively on about five different rolamite devices--electromechanical accelerometers, g sensing devices, and things of this nature. "To give you an idea of the versatility of rolamite in sensing inertial fields, I will illustrate two different types of integrating accelerometers that we have been working on. We have worked with three ways to provide damping in an integrating accelerometer. We use a gas to damp the roller cluster and pump air from one chamber to another. We use incompressible fluid such as silicone oil and pump it from one chamber to another. A third way that we've conceived of providing a damping function is to turn rolamite into a mechanical verge escapement."

INTEGRATING ACCELEROMETERS

* * *

VERGE ESCAPEMENT

Figure 1 shows one version of a rolamite verge escapement. In this configuration the verge mass is shown at A. This mass must be free to oscillate about a center at B. One side pin of the verge mass is forced into the "valley" or tooth root of escape wheel C and one side pin is forced up to the "hill" or tooth tip of escape wheel D. Escape wheels C and D are necessarily 1/2 tooth out of phase with one another. As the roller cluster moves left or right the side pins on the verge mass alternately engage the tooth roots and tooth tips on escape wheels C and D and also alternately cam up the tooth surfaces of escape wheels C and D causing the verge mass to oscillate at a rate approximately proportional to the torque applied to escape wheels C and D.

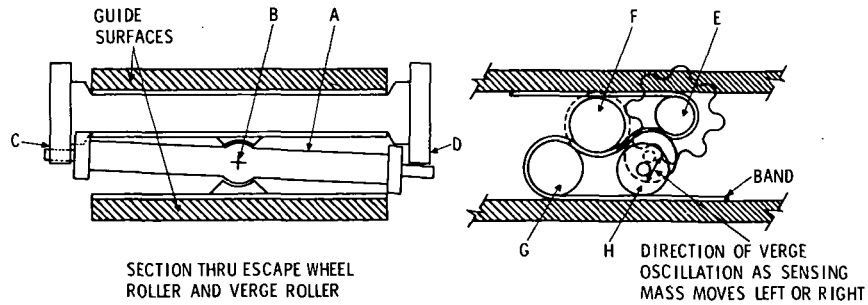

Figure 1. Verge Escapement

The four rollers, E, F, G, and H, verge mass A, and escape wheels C and D--in fact all masses except guide surfaces--perform a sensing mass function. The ratio between the diameter of roller E and escape wheels C and D controls the ratio of the surface velocity of

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escape wheels C and D versus the velocity of the roller cluster. The number of escape wheel teeth passing by the verge mass side pins, the weight of the total sensing mass, and the inertia of the verge mass all are factors determining the damping function the device can perform. Roller F, by the addition of appropriately designed flanges, also serves the useful function of guiding the verge mass to assure that its oscillation is restricted to a curved plane approximately perpendicular to the centers of escape wheels C and D.

* * *

SWITCHING--BAND CONTACT

A workshop question period began with a discussion of electrical contacting via the band. Contacting directly with the bands is a poor idea except with very small currents. Ten amps will probably cause arcing, which may actually take pieces out of the bands and will heat the bands locally around the contact area, causing the mechanical stresses to be extremely strange around the contact area. There are ways of designing contacts in the rolamite for a large number of cycles in contacting, but it probably means introducing some additional contacting members for high current.

* * *

RIVET CONTACTS

For an added contacting member on the band, a precious metal rivet would add some mass. Such members could be allowed to burn away to raise the life expectancy of the contact.

* * *

BAND CURRENT CARRYING CAPACITY

The current carrying capacity of the band must be an important design consideration. If the band is used as a conductive element, its use for one cycle to turn something on and off only once is far different from having the same thing happening repeatedly until the system reaches an equilibrium temperature. Often the band is not a very good current-carrying material; for instance, beryllium copper, the material which should probably be used for this type of system, has about 25 percent of the conductivity of copper. Just about all the good spring materials are 7 percent of copper or lower in conductivity. In the amp range at 110 volts, significant heating occurs, and should be taken into account by redesigning the contacting members. The design should allow for the heat to dissipate. Duimstra pointed out that one of his calculations "showed that a stainless band of the size you might want to use in a small electromechanical device under the conditions described (quite a few amps at 110 volts) could dissipate a few watts, provided the thin band was heat sinked well to the case wall."

* * *

INCREASING CURRENT CARRYING CAPACITY

Conductivity of bands can be increased by plating. However, in electroplating metal on the band in significant thicknesses, the thickness must be such that the stresses in the band and plating are not any greater than that which can be tolerated by the materials involved. A thin gold coating on a beryllium copper band is not going to change the other properties that are necessary for a return spring or the like. As Duimstra defined it, the problem is size-related. "If you're talking about a large rolamite with a heavy band and a lot of width, you can get much more current down the cross section of the band than you could with a small device. As a matter

LIMITATIONS

of fact, we had a problem in current carrying capacity with a device at Sandia. We were planning on laminating a band and putting conductors within two pieces of plastic. The conductors were carried with the rollers so that, at the end of cluster travel, a bare place on the plastic allowed the conductors to contact. But it turned out that, by using this method, we were overheating the plastic and causing delamination and melting of the plastic material because the current was too high. In the devices we're concerned with at Sandia, we're not talking about millions of operating cycles, so our contacting problems are a little bit less severe."

LIMITATIONS--MATERIAL TRANSFER

Another problem that occurred to several people was that of assuring that the arcing (taking place between the roller or band and the stationary contact) could not cause metal splatter where it might interfere with the rolling action.

CONTACT WIPING

Among contacting arrangements which might be used are grooved contact and the band "tab" concept, mentioned in Wilkes' rolamite literature. These concepts cause a controlled amount of rubbing to occur on contacting. This will have a beneficial effect of clearing away contaminants so that low-resistance, metal-to-metal contact can be made. Actually, these rolamite contacting problems are very similar to contacting problems that people had in the past with ordinary relays.

SLIPPAGE

There may be an advantage to having a contact all the way around the roller. If microslip does occur during each cycle, a new contact surface will be presented to be used at each operation. This might make possible a cost savings by making a thinner layer of contact material on the roller, so that a slippage can be turned into an advantage.

SWITCH ACTUATION

Questions on switch actuation with differential tabs from the band and by external forces on the roller were mostly deferred to an afternoon discussion group, Dr. Diller's workshop B-2 on Electrical Switching.

* * *

ROLAMITES USING MAGNETIC EFFECTS

In reply to a question about putting magnetic fields around rolamite clusters, Chairman Duimstra summarized a number of ways in which magnetic circuits can be used in conjunction with rolamite. There are illustrations on how magnetic circuits might be utilized in rolamite geometry in SC-RR-67-657A, D. Wilkes' research report on the rolamite. The rollers themselves can be electromagnets, or one can make the rollers of soft magnetic materials and place electromagnets external to the rollers. There are a large variety of possibilities in utilizing the rolamite suspension in electromagnetic circuits, including some relay models already constructed at Sandia.

* * *

DISPLAY SYSTEMS

One participant was particularly interested in the display devices which showed take-off from a diaphragm or differential. Some of the display devices show linear forms, curves, continuous rotation, multiple needle presentation and the like. Developing the topic, Chairman Duimstra pointed out, "Using the rolamite suspension system for presenting information through a needle-dial system we get

NEEDLE DIAL

some interesting action. By simply attaching a needle to one of the rollers in the rolamite suspension, any point on the needle will circumscribe a trochoidal motion. Over a portion of the trochoidal curve a fairly flat motion results so that in a voltmeter or something of this nature, the center of action would be closer to the point of the needle and you can get your needle to travel a long distance. This would result in a compact meter dial arrangement with good resolution (see Figure 2).

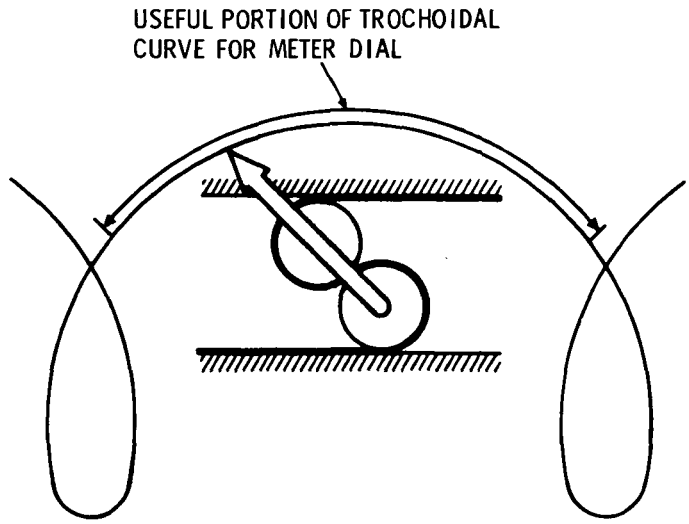


Figure 2. Rolamite Meter Suspension

USING CUTOUTS AND BIAS

"Of course, you must not forget the accessory benefits you could get from rolamite, such as configuring the band to provide spring biasing in a return direction. The spring biasing could be configured to exactly compensate for whatever variances you have in the measuring system; for instance, if you have a DB meter on a log-log scale, you could compensate for the log-log and get it to work on a linear system simply by biasing the return spring in the proper fashion. Another advantage of a rolamite meter suspension system over a conventional needle bearing system would be its reduced susceptibility to shock and vibration."

SUBSTITUTES FOR BAND SUSPENSION

As Ed Ralston (IBM) pointed out, very often one doesn't need the force generation characteristics the band has to offer, but still needs millions and millions of cycles. "Has anybody ever experimented with a series of cables as a suspension system?," he wondered. "Could you get longer fatigue life out of the device in this manner?" The consensus was that it is certainly possible to band a rolamite in this fashion. However, if the cables are single stranded cable, they would have to be of nearly the same thickness as a band because of the fact that the outer fibers would be stressed the same going over the outside curvature of the rollers. Stranded cable may help the situation. However, stranded cable would generate friction within the cable strands as they move along one another.

ELIMINATING BAND

In relation to different methods of suspending rollers, Duimstra mentioned a device which Don Wilkes built not using any band.

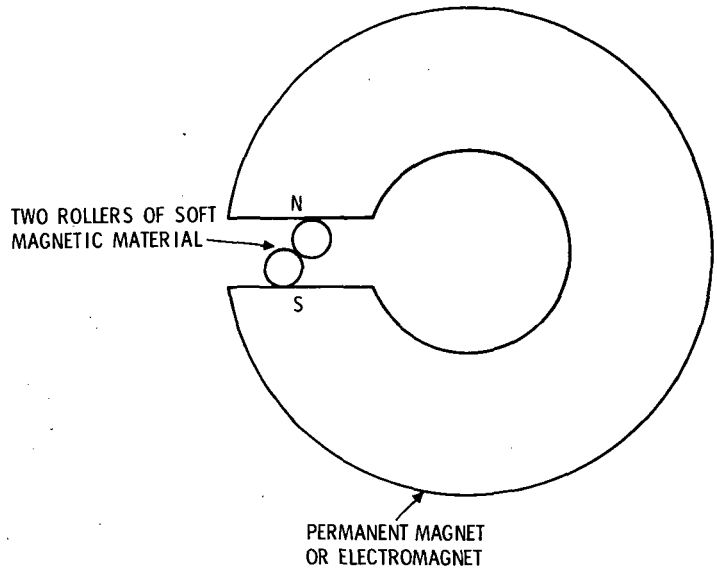


Figure 3. Bandless Rolamite Geometry

If one applies a magnetic field between two guide surfaces and puts two rollers between the surfaces, they automatically assume a rolamite geometry. A fairly linear magnetic field will provide a very friction-free travel of the rolamite cluster without any band at all.

N76-19451

APPLICATIONS WORKSHOP III-A-4

FLUID DEVICES

Reginald Scroop, Rolamite Technology, Inc., Chairman
Workshop Consultants: G. B. Wilkes (RTI),
William Gruber (Technar), and Jack Leroy (SL)

ROLAMITE VALVES

William Gruber began the workshop session by describing Technar's use of rolamite as a valve. The mechanism shown in Figure 1 is housed in a fluid-tight enclosure. When the magnet on the left is energized, the rollers are pulled toward it and the band rolls over the outlet port. The pressure within the device then forces the band down against the port and leads to high sealing forces. When the magnet on the right is energized, the cluster moves to the right and a very large mechanical advantage is available to peel the band from the outlet.

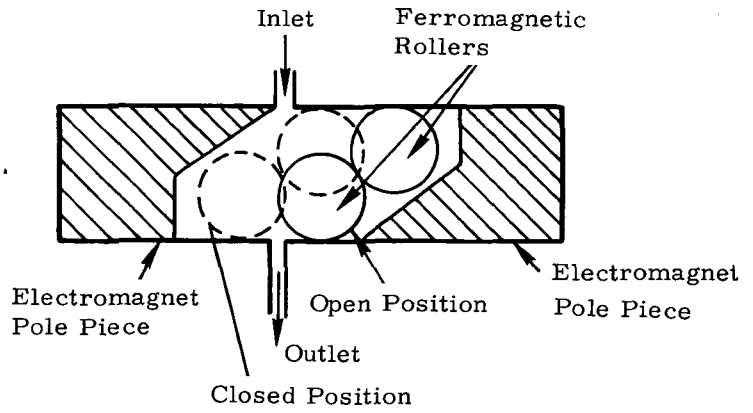


Figure 1. Technar Rolamite Valve

VALVE OPERATING CHARACTERISTICS

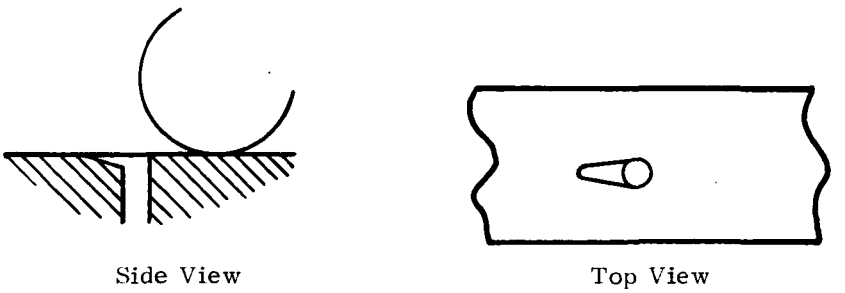
Although Technar has taken no particular precautions to obtain a good seal, they obtained leak rates of 6.5×10^{-4} of maximum flow rate for a 1.6 gpm valve and 2×10^{-4} for a 0.2 gpm valve. The materials were stainless steel bands operating over rollways made of acrylic in the former case and brass in the latter. Water at 80 psig was used in both cases.

GENERAL CHARACTERISTICS

The advantages of such a valve include high sealing forces and low actuating forces coupled with the absence of moving seals in the case of an electromagnetically actuated valve. It seems particularly attractive at the extremes of temperature or in the absence of lubricants.

COANDA EFFECT

An interesting complication arises from the Coanda forces created when the fluid moves past the curved roller surface near the outlet port. The forces are such that the rollers are pulled over the outlet and the device tends to shut itself off. However, by contouring the outlet port as shown in Figure 2 the magnitude of these forces has been reduced substantially.



Side View Top View

Figure 2. Contouring for Coanda Forces

ACTUATION

Problems encountered in valve development include the difficulty of mechanical actuation and the inefficient magnetic circuit. Furthermore, the device operates satisfactorily only with unidirectional flow.

ACTUATING POWER

A jet pipe servo flapper could probably perform the functions of this valve, but the actuating forces are likely to be a good deal larger.

PROPORTIONAL CONTROL

Technar's prototype valves to date have all been on-off devices. It would be possible to make a proportioning valve by contouring the outlet as shown, but then there arise problems of cluster positioning.

FREQUENCY RESPONSE OF VALVE

The maximum operating frequency of the electromagnetic valve is 15 Hz. The band is constructed with an additional leaf at each end which gives the roller cluster an equilibrium position near the middle of its travel. The natural frequency for oscillation about this equilibrium is about 15 Hz.

ROLAMITE FLUID DEVICES

In beginning the discussion of what role rolamite has to play in fluid device technology, H. A. Brunner (Reynolds Metals) commented that rolamite is up against very stiff competition in the pneumatic control field. There is now on the market a spool valve which has extremely close tolerances and requires no lubrication to operate for at least 20 million cycles. The device is immune to contamination because the sharp edges on the spool just grind up the particles. It competes very well with fluidics because it is so reliable.

Chairman Scroop pointed out that rolamite devices would offer much easier manufacture—assuming, of course, that they could perform the same job. He went on, "I would like to ask if anyone has any

thoughts about using rolamite either for an impedance-matching device in fluid circuits or at the interface between fluidic and mechanical elements."

* * *

ACCELEROMETERS

Jack Leroy pointed out that it seems premature to give rolamite a specific role. However, Sandia is pursuing development of fluid-filled rolamites which integrate acceleration to obtain velocity. Leroy described a method Sandia uses to meter fluid: by means of a tube connecting the ends of a closed rolamite channel which contains the fluid to be metered (Figure 3).

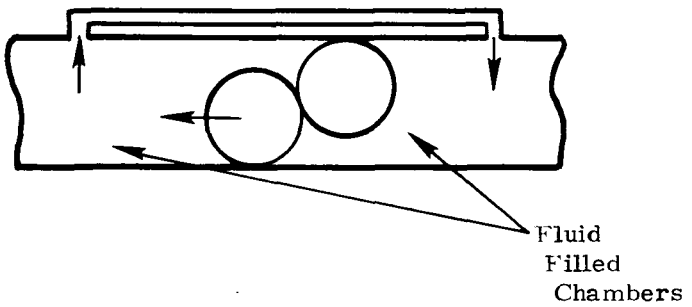


Figure 3. Sandia Fluidic Accelerometer

The application is a missile launch, so g forces are used to actuate the device.

* * *

SIGNAL AMPLIFICATION

General Electric has been doing considerable work in fluidics; one of their problems has been amplifying signals to useful levels in pressure ratio sensors flowing hot gas. One is usually dealing with rather low pressure differentials in the neighborhood of 2 psi or lower. A nearly frictionless device such as rolamite appears attractive as a means of making the transition from the pressure signal to a mechanical output. GE is presently using torsion bars which are difficult to manufacture because of the small forces involved. Although the rolamite principle has not been tried in applications of this kind, it looks feasible and well worth investigating.

* * *

USING INHERENT LOW-FRICTION ADVANTAGES

G. B. Wilkes agreed that if one hopes to use a rolamite, its inherent low friction should be exploited. For example, if one is working with very low pressures, the rolamite could be an attitude functional device whose position depends upon the pressure within a bellows, say, attached to one end. When the pressure achieved a predetermined value, the cluster would move and perform a switching or other signalling function.

PROBLEMS WITH FLUID DEVICES -- END SEALING

When one considers sealing around a rolamite cluster, there are no problems with respect to the lines of contact along the rollers.

Even if the geometry is not particularly tight, tension makes a seal between the band and rollers. The ends of the rollers, however, present a much more formidable sealing problem. In typical applications, the end gaps must be kept below 0.0005 to 0.001 inch for gases and 0.005 to 0.004 inch for water. You can see that some expensive machining is necessary in order to obtain true sidewalls.

TOLERANCES

Wilkes proposed what he felt was the best way of solving the general problem of end sealing. One can make rollers with a slightly beveled end that fit in a channel with beveled sidewalls, as shown in Figure 4.

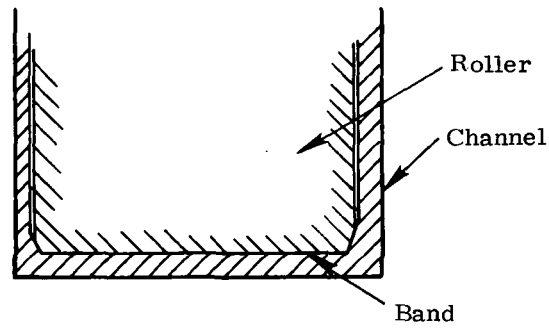


Figure 4. Beveled Sidewalls

This almost eliminates short leakage paths near the points where the rollers are tangent to the channel. In addition, the roller can be spring-loaded to take up any tolerances in the length so that one need only put a bit of quality control into making the angles correctly.

As an example, RTI built a rolamite using an extremely accurate electroformed channel with two tungsten carbide rollers 1/2 inch in diameter and 3/4 inch long. With the end of the channel closed off, it took 7 minutes for the rollers to fall an inch under gravity.

The effects of leakage can be reduced further simply by making the rollers longer. In this way the leakage is kept constant while such things as the swept volume and forces due to pressure gradients across the roller cluster can be made large.

Jack Leroy added that Sandia's approach to end sealing is to minimize the end clearances within the context of efficient manufacture. Then they adjust the viscosity of the oil and the orifice size so that flow past the roller tips is negligible. Tests are under way to define the success of this technique.

SIDEWALL ORIFICE CONSTRUCTION

Minimizing the orifice is related to the means used to prevent the rollers from rubbing on the channel sidewalls. Since initial rolamite work, many have assumed that the best way is to provide angles in the channel. However, Sandia is beginning experiments to determine whether or not oil will keep the rollers from touching the sidewalls so that no angle is required. Obtaining this angle may be the single biggest problem in manufacturing cases, so its elimination could be significant.

omit

APPLICATIONS WORKSHOP III-A-5

THEORY AND FORCE GENERATION

R. V. Cadman, Sandia Laboratories, Chairman
Workshop Consultants: C. M. Percival (SL) and F. R. Norwood (SL)

SWITCH ACTIVATION ENERGIES

As a design example, a rolamite tilt switch was discussed. Two questions were:

1. Will the cluster have enough kinetic energy to actuate a switch at the end of its travel? Since the cluster starts from rest (latched at the "high" end) and will again be at rest after actuating the switch, an energy method appears to be the easiest way to answer this question. The kinetic energy and the dynamics of the problem could then be ignored.

OPTIMUM ANGLE OF REPOSE

2. What angle of repose is optimum? Although no one was aware of a definite theoretical answer to this question, it was agreed that the band tension and angle of repose should be adjusted to give the best compromise between high normal force for contact pressure, high friction between band and rollers to withstand inertial loads, and low rolling friction.

* * *

BAND SLIPPAGE

The question of slippage between the rollers and the band was discussed at length. Several schemes were proposed to completely prevent slippage. For small cluster travel compared to the "wetted perimeter" (length of band in contact with one roller), the band could be pinned to the rollers. For larger travels, rows of holes might be etched in the band (similar to the holes in motion picture film) and the rollers provided with sprocket teeth. If both rollers had rows of teeth, they would have to be mismatched. Gear-shaped rollers might also be used to mate a "timing belt" type of band. However, in etched metal bands, it might be difficult to etch the necessary thickness variations. Sufficient band tension will prevent slippage between "smooth" bands and rollers, at least for a few cycles of motion. More analysis and experimental work is needed to determine the amount of band tension necessary to accomplish this, if the load tends to cause the slipping.

* * *

MANUFACTURING TOLERANCES

The dimensional and surface finish tolerances were discussed briefly. Glass cases are being used on some of the Sandia designs, partly for tolerance reasons. There were no precise quantitative answers to this question.

* * *

PREDICTING FORCE GENERATION

Design experience has shown that the level of the forces generated by cutouts in the band cannot be predicted accurately. The uncertainty is typically ±15 percent. Much of this uncertainty is due to variations in band thickness. Typical thickness tolerances are

±5 percent, and since the band-generated force is proportional to thickness cubed, thickness tolerances alone could account for the force level uncertainty. Typical rolamite bands are very wide compared to the thickness, and thus should probably be analyzed as plates rather than as beams. A plate effect, or Poisson effect, would tend to increase the force level roughly 7 to 14 percent above that predicted by beam bending analysis. Partly because of the uncertainty in band thickness, this plate effect has not been studied experimentally for rolamites. It was suggested that radiation thickness gages could be used to measure the band thickness more precisely. If perforations are used, rather than a full cutout, the perforation shape and pattern and the percent area removed will all affect the force level. These effects have not been studied extensively. It appears that it is possible to have perforations which do not significantly lower the force level. There was some discussions of design schemes, other than individual calibration, which might reduce the force level uncertainty.

Several areas requiring further study were mentioned. One not mentioned previously is the effect of band cutouts on frictional behavior.

N76-19452

APPLICATIONS WORKSHOP III-B-1

MATERIAL AND METALLURGY

Marlin S. Walmer, Hamilton Watch Company, Chairman
Workshop Consultant: Sherry Holmes (SL)

* * *

Mario Di Giovanni, Statham Instruments was particularly interested in transducers and suspension-type instruments exposed to saline solutions of the human body. Havar Elgiloy, or titanium alloys would be the best material for rolamite bands in this kind of environment.

CORROSION OF MATERIALS

In a discussion of fretting corrosion in rolamite mechanisms, Don Wilkes pointed out, "Any highly stressed material, such as a rolamite band in the area of the bend where it is in contact with the rollers, is vulnerable to stress corrosion. If the environment is corrosive, the design should include a sealed chamber. It would be appropriate also to consider a very thin coating of plastics to seal the band from the environment. Since plastics typically have a modulus of about one fiftieth to one one-hundredth of steel, the effect of the thin plastic on the stiffness of the band would be negligible. It is also appropriate to consider using dry lubricant films to minimize the possibility of fretting corrosion and cold welding."

* * *

BAND LUBRICATION

In reply to Mr. Martin's suggestion that a lubricant would decrease the torque required to cause slippage between the band and roller, Wilkes agreed. However, in most of his applications slippage was not a problem, since they were low motion devices with the band pinned to the roller.

* * *

PROPER BAND ATTACHMENT

In experimenting with Havar, Statham had been having problems with breakage at the point of attachment. Mr. Walmer suggested that when attachment involves a pin through a hole in the band, very high stress levels can be encountered at the point of contact of the band with the pin. One method of band attachment involves the use of a threaded pin. After the band is in place, a thin plastic washer is slipped down over the pin and the band is clamped using a nut similar to those used on a No. 6 dry cell. This method eliminates point contact of the band against the pin and prevents the high localized stress which causes bands to tear out at the hole.

Mr. Walmer gave the calculation for the minimum bend radius for a rolamite band using the formula

$$t_{max} = \frac{\sigma_y d}{E - \sigma_y}.$$

Since the yield stress is small compared to the modulus, the formula becomes

$$t_{max} = \frac{\sigma_y d}{E}.$$

* * *

Ernesto Martin, Communications Satellite Corporation, who expressed a need for low rpm rolamite bearings for infinite lifetime without lubrication, asked about present production of endless bands.

ENDLESS BAND PRODUCTION ROLLING

Dr. Polokowski at the Illinois Institute of Technology, Chicago, is working on a process to make endless bands for any application which would require them. A sample of one of the first bands that he made was on display. Professor Polokowski's method consists of starting with a piece of tubing which is slipped over one roll of a rolling mill. As the rolling proceeds, the band lengthens and gets thinner. There is no weld joint if the starting material is seamless tubing. If welded tubing is used, the repeated cold-working and annealing during the process erases the weld.

These bands are not yet a production item, but endless bands to thicknesses of 0.002 inch look feasible. Problems which have to be solved are crown across the strip, and waviness.

* * *

ELECTRODEPOSIT

Sherry Holmes added that endless belts can be made by electrodepositing nickel or high nickel alloys on an aluminum cylinder. Then, after etching away the aluminum, a flat, endless band remains. This would be suitable for making endless bands where high strength is not a requirement. Sandia had also, using this process, made a bellows which exhibited no mechanical hysteresis.

* * *

In reply to a question by Martin, RTI's Don Wilkes agreed that cold welding would occur to a certain degree in rolamite applications in outer space.

FAILURE MODES OF BANDS IN SPACE APPLICATIONS

When the roller moves off the point of weld, said Wilkes, "you might have a detent effect produced to some extent but it would be slight, since the weld projection would open a small depression on the opposite side. A reasonably tight geometry allows essentially no slippage between band and rollers; the projection and depression always match up, causing little, if any, detenting action."

Because of the small size of cold-weld points compared to the functional cross-section area of the band, broken cold-weld points do not measurably weaken the band. Wilkes pointed out that some materials are more likely to weld than others; beryllium copper would be one that is not likely to cold-weld.

APPLICATIONS WORKSHOP III-B-2

ELECTRICAL SWITCHING

N76-19453

R. W. Diller, Technar, Inc., Chairman
Workshop Consultants: C. H. Rahe (Hamilton); G. B. Wilkes (RTI); and D. O. Schuler (SL)

ROLAMITE SWITCH CAPABILITIES

Discussion of rolamite switching began with the general feeling that rolamite is best applied when something more than snap switching is required, as in velocity switches, acceleration switches, or gravity switches. Rolamite switches can sense environments--any kind of force, specifically things like velocity and distance, pressure, acceleration, temperature, or time. Rolamite becomes extremely attractive if one is interested in having the switch do something else besides push-button switching.

ECONOMICS OF ROLAMITE SWITCHES

Robert Diller discussed the economics of rolamite used as a simple switch. "I think that a simple economic example would be instructive. First of all, you are competing with switches that cost on the order of 50 cents. The case is going to cost a few cents, say a nickel; a roller may cost a nickel; the band is going to cost a nickel; and assembly is going to cost a nickel. Contacts will probably cost a dime, so right away you have laid out 35 cents. Then you try to sell this to the distributor and he is going to try to make some money. Even considering that all these things are a really rough estimate of the cost, you have already priced yourself out of the market, particularly if you do something like make a cutout of the bands or preform a band. If you are going to make a snap switch, you want high acceleration for your switch; typical accelerations in existing snap switches are 200 to 250 g's. Rolamite devices accelerate on the order of 10 g's maybe 50 g's; beyond that you have problems; so in building a snap switch, again here is something that makes rolamite less attractive.

"Now if you are willing to go further and use the rolamite as something else, with switching as a primary feature or an incidental feature, then chances are that you can sell this thing for a lot more and tolerate the additional expense."

SEQUENCE SWITCHING

Dick Ralston inquired about problems involved in the design of rolamite for sequence switching. Technar's design did not put the printed circuit on the band, but on a printed six-channel circuit on a guide surface. Technar prefers not to alter the band, because that increases the cost of the band considerably. At high currents, arcing completely destroys the printed circuit. At low currents there are problems involved in making good contacts and maintaining the reliability over the expected lifetime of the device. There is the contamination of guide surfaces either with little particles or organic film. The only way to get rid of the film is to push down on the contacts by putting tension on the band to get a tight geometry with a large angle of repose. To get rid of granular contaminants they seal it, not necessarily hermetically, but at least with a dust cover.

TECHNAR SEQUENCE SWITCH WITH GUIDE SURFACE CONTACTS

SANDIA SEQUENCE SWITCH WITH BAND CONTACTS

Douglas Schuler described Sandia's work using contacts on the bands. "A lot of problems are being investigated in this area. One is that your laminate buildup may be very great, of the order of 3 or mils, while the band is 1 mil. Also, we were having trouble with ours after several hundred cycles, when the laminates tend to pull apart. If you can find the right type of adhesive, a viscoelastic type, the possibility of controlling this is enhanced. You might actually build a damping device with a viscoelastic material as part of your adhesive buildup. What we were doing was to insulate the band at the bottom with contacts on the top. We had six contacts with cutouts in the spaces between the contacts to generate our force. So we had our force generation and contact sequential switching all in one device."

BAND VERSUS ROLLER CONTACT

Robert Diller pointed out some objections to making contact on the band by laminating the contacts. "If you are going to be switching currents of a few amps you are going to get arcing on the band and thus get localized heating of the band. Just the action of the band bumping up against the contacts over and over again for many, many cycles is going to deform the band locally. Both these things contribute to reducing the effective life of the band. If you are interested in applications requiring operation for many millions of cycles, you cannot tolerate this at all. At Sandia they are interested primarily in devices that operate a few hundred times, so this is not so critical. Nevertheless, because of these problems in reducing the endurance strength of the band by putting contacts on it, and because there are problems in putting contacts on the band, it would seem reasonable to put the contacts somewhere else.

HIGH CURRENT RELAY

"We had suggested earlier this morning to consider using the roller--it is available, it is massive, you can plate it, you can laminate it, there are lots of things you can do to put your contact material on it. Further, the mating contacts on the guide surface are much easier to prepare. Such techniques will not affect the useful life of the band material. The roller is significantly more massive than an ordinary contact even in a high current relay. You might consider using that great big massive contact as a place to dissipate heat, as a place to take arcing wear and other kinds of electrical wear, and build the entire function right in to the rolamite device. Instead of electrically actuating the relay, it is conceivable, in principle, that you could just build a 50-amp switch which would be actuated somehow, hopefully with low force, low travel, and all that you would like a smaller switch to be. In such a power relay you get a chance to combine more functions with rolamite."

TECHNAR ENCODER

In response to a participant's question about Technar's encoder, Diller described the design which allowed the roller to protrude through the band cutout in order to short to the guide surface. "A cutout provided linear spring force so that the thing would go back and forth in a fashion that was interesting to us. And because of this cutout it was easy just to allow the roller to protrude through that cutout and touch the guide surface. But you do not have to make a cutout in the band to do that. You can have the band in one region and the contact on the end, so that the band may be rather narrow, and out at the end you have the contact pattern and a place where the rollers mesh. If you are not interested in coding or commutating, but just in switching, then the switch contacts need not be on the ends nor do they need to protrude through the band because you can arrange it differently (Figure 1). You can put a contact over here where the roller goes up and touches it. You can make it "spongy" if you like, to possibly eliminate some bounce. If the contacts bounced with a characteristic frequency, you could change the springiness to get rid of the entire problem."

ALTERNATIVE SWITCH CONTACT POINTS

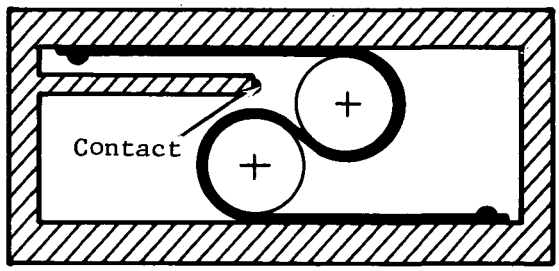


Figure 1

* * *

GENERATING CONTACT FORCE

Diller went on to say that contact force in a commercial encoder might be provided by a spring-loaded guide surface. The roller pushes it down flush with the rest to get reasonable contact pressure. Once on top of the contact, normal forces of the rolamite geometry would be rather substantial.

* * *

COMPOSITE ROLLERS

Discussion of the complexity of manufacture of composite rollers or laminated rollers resulted from a participant's application in telephone switching, which required several distinct functions in a single package. Using the roller as a common contact would evidently simplify the device and lower its costs. The rollers may be laminated from inexpensive screw machine parts held together coaxially. Printed circuits on the guide surface are inexpensive (two or three dollars).

SEQUENCE SWITCHING WITH SPOOL ROLLERS

Douglas Schuler presented a Sandia design which incorporates a type of sequential switching. "Our problem was to design a switch to give momentary closure at two distinct acceleration levels. Our solution was to use spool-shaped rollers as shown in Figure 2.

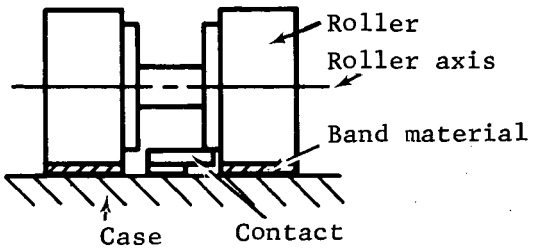


Figure 2

"The band runs on the outer spool of the rollers. The band and rollers form one part of the electrical circuit. The rest of the circuitry comes from a beryllium copper and Mylar laminate which is inserted the length of the case between the spooled sections of the roller. The copper and Mylar insert has two cantilever tabs extending so that the inner spool of the roller will roll across only the tab. The tabs are positioned to correspond to the roller position in the case at the two acceleration levels where closure is desired. As the roller travels down the case it will roll over first one tab and then the other, producing two distinct, momentary contact closures.

"One advantage of this type of contact arrangement is that the electrical functions are carried out by the insert, band, and rollers. The case can contain purely mechanical guiding surfaces. The circuitry on the insert can be made simply and cheaply, using existing photochemical etching techniques. Another advantage is the differential sliding action which occurs between the contact tab and the inner spool of the roller. This wiping action occurs because the portion of the roller which touches the tab is moving at a different linear velocity than the outside of the roller. This action should clean any oxide films off the contacting surfaces.

"The above method is one way of getting a type of sequential switching without having to go to the added expense of laminated roller bands or having to cut access holes or slots in the case to allow for external contacting methods."

* * *

SIDE CONTACTING WITH ROLLERS

Schuler pointed out another contacting alternative when the rollers are used as part of the electrical circuit. By placing the contacts at the sides of the rollers and at a radius other than the roller radius, it is possible to get the same contact pressure as the roller has against the case, with the added advantage of a sliding action between the roller and the contact.

SANDIA INERTIAL DEVICES

Most of Sandia's use of rolamite is in the field of inertial devices, with electrical switching of secondary importance. Using rolamite allows them to tailor the force characteristics of the device to match the specific application in mind. In these applications the rollers function mainly as an inertial mass. The prime interest, to date, at Sandia is in the ability to tailor the inertial response of a rolamite to suit their needs.

SOLENOIDS

Some work has been done using rolamite as a solenoid. In this application the coil is wrapped around one end of the case. The rollers are made from magnetic materials, and the band force is tailored so that when the coil is de-energized the switch will snap to the other end. Re-energizing the coil will cause the rollers to return to their original position. This work has been done only on an experimental basis with limited success.

RESETTABLE CIRCUIT BREAKERS

Interest was expressed in a rolamite device for circuit protection, with manually or automatically resettable breakers. With thermal switches using bimetallic bands, self-repairing fuses seemed feasible, but no one had a design to present.

* * *

CONTACT MATERIALS

Diller described the wide variety of available contact materials. "The most noticeable differences arise from variations in the amount of current that you wish to switch, arcing, and things like that. With rather delicate items like encoders or instrument-type switches, we feel that you can use precious metals in thin layers. There are many kinds of materials that people like the Ney Company can come up with that are supposed to be quite suitable for this sort of thing. On the other hand, when you start talking about switching currents not of the order of a few milliamps to a hundred milliamps but of the order of a few amps, then silver or precious metals alone cannot be used in contacts universally. There are some more exotic materials which end up costing a small fortune, like silver-tungsten alloys or copper-carbon alloys. A host of these things that come out of powder metallurgy are of interest when you are trying to switch very, very high currents."

* * *

ELECTRO-MECHANICAL DEVICE MATERIALS

Technar has been working on beryllium copper for electromechanical devices, Diller went on to say. "I understand there is a proprietary material available from Olin, Olin alloy 194, which exhibits very fine electromechanical wear properties. I do not believe that it is particularly a spring material, but in moving joints in electromechanical devices where you do have electricity passing through the joint, you are going to get some heating. We at least think that is what happens; it is the heating from slight arcing, or just from resistive heating. But it is tending to elevate the temperature of the material to a point where its wear properties are degraded. According to Olin their material has fine wear characteristics at slightly elevated temperatures and it is particularly suited for moving electrical joints. As a contact material, though, I do not know that it is particularly great. It is primarily for joints.

OXIDE FORMATION

In a high current relay, a participant had a special problem with oxide formation. His question: "What can rolamite do for us?" With a rolamite device, it was suggested, he could make the geometry sufficiently tight so that normal force would break through the oxide. Silver-tungsten was also suggested as a substitute for silver-cad oxide, which he had been using.

* * *

DESIGNING WITH ROLAMITE

In suggesting approaches to the whole concept of electrical switching design, Gordon Wilkes pointed out, "I think that with rolamite you have changed the name of the game. In the past we have been stuck with rates of contact approach and rates of wear or rubbing and things like this that you have got to live with. Either you have a linear sliding of a wiping element, or you have flush contacting where you have a slight amount of wiping that comes about by channeling the beam action or something like this. Rolamite changes the whole thing. By using the differential behavior you can independently work on the rate of closure and the amount of wear. Instead of trying to think of how to get two contacts to come together and do this, decide what kind of action it would take to accomplish this. In your case you have a high current for a limited number of cycles and you know what your problem has been with the way you did it before. If you decide what the ingredients for a successful solution would be, then you could probably find a way of manipulating the rolamite to do this.

"I want to point out one other thing. You are not bound by circular rolling. In electrical contacting devices, all you are trying to do is close contacts. You are not talking about large distances. So rather than worry about the inherent coupled inertias, think of other qualified shapes. You see, I think maybe some of you have seen rollers that are constant diameter figures with varying curvatures. Have you ever seen these things? (Figure 3) You take a radius here (R_1) and then another radius out here (R_2). You see, if I measure anwhere across here (X) I would get exactly the same dimension.

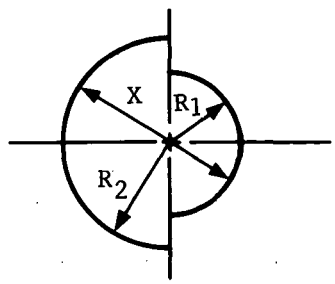


Figure 3

You can get rolamite rollers this way, and in doing this you get very high rates of closure and very low inertias coupled together; they work very well for a small motion like you might need in switching. So, if you really want to get something out of this, don't stick in a rigid framework. Don't make a direct analogy.

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Find out what is wrong with the way you are doing it now, and then use all the tools you have immediately available to try to work out what would be a more idealistic way of going about it. You probably could do it pretty well."

SWITCH ACTIVATION TECHNIQUES

Chairman Diller proposed that the workshop consider various ways of activating a rolamite switch, assuming it is not activated by itself. "How do you move the rollers? You can move them with a tongue or rod to push the roller cluster back and forth. You can also move the channel back and forth and keep the rollers stationary. You can turn the rollers. There are a number of possibilities. All of them involve somehow getting out to the outside world. If you have contaminants fouling up your electrical contacts, this looks like a big problem: how to seal this thing sufficiently and yet get into it. If you use some kind of grease seal or dust seal, you are introducing some friction that you may have decided you wanted to reduce by looking at rolamite.

ELECTROMAGNET ACTIVATION

"An electromagnet seems to work adequately, but it seems unfortunate to have something as complicated as an electromagnetic device to get the thing actuated when it has all these mechanical couplings."

PERMANENT-MAGNET ACTIVATION

"Technar has experimented a little with permanent magnets. One problem you might run into is that, if you are trying to make something small, the magnets you have on the outside end up being rather large in comparison to what you would like them to be for that size device. With this permanent magnet that you have on the outside you are going to be moving it in such a way that the magnetic circuit, so to speak, is not always complete. If you are going to use something like Alnico with any of the ordinary nickel-type magnets and you decouple the permanent magnets from the magnetic circuit, you lose a tremendous amount of the residual B-field. So what you begin looking for, then, are ceramic magnets which are designed to have very high residual B. What this means for you, unfortunately, is that nobody has made ceramic magnets with the same density of attracting force as we have in Alnico magnets. So you are going to end up with a slightly larger magnet because of the fact you have to move the thing. If you can manage to build your magnetic circuit in such a way that when you move it to actuate the switch, you move it from one portion of the magnetic circuit to the other, the problem can be minimized. Then you might be able to get away with using an Alnico magnet, which, being smaller, might be more appealing."

BAND DEFORMATION FORCES

Another suggested way of getting the rollers to move was to bend the band with the application of voltage and thus force the rollers to move. Materials are available that deform with the application of a few volts. However, the force is small and would only move small rollers unsuitable for switching high currents.

BAND DEFORMATION PROBLEMS

In reply to the question, "How much deformation can a band stand without failing to operate?" Diller replied, "None. You should probably never operate the device above the yield stress of the material, because, as Dr. Bell pointed out in his lecture yesterday afternoon, it takes energy to deform it and you do not get this energy back. It is dissipated in the form of heat in the band. You may be able to tolerate the fact that the band has changed. You may not be able to tolerate the fact that you lost energy doing it. With enough actuating force, it will work eventually, though it will not last as long. One thing, is that when the band contains a permanent deformation it will generate a force. If you have a device that you may want to operate once, a one-shot device, you could consider operating above the yield limit and use it as an energy-absorbing device.

"Again, if you are interested in more than one operation, but not many, then you can operate close to the yield strength; but if you want it to last a long, long time, then you have to go down to the endurance strength of the material, which is generally one-third to one-quarter the size of the yield stress."

* * *

SUMMARY

The session participants were most interested in contacts and switching combinations. A better use of rolamite involves performing functions in addition to switching. Information on contacts has been limited by the lack of technology: with current methods of switching, companies are not studying the rolamite designer's problems with purely rolling contacts or the sliding necessary to eliminate contamination problems.

Dick Ralston's comment was that "rolamite is really going to shine when the application uses it as an electromechanical device, a switch, and a transducer, all in one little lump."

Chairman Diller agreed, concluding, "I think one thing we all learned from the whole conference is that you are right. We have to look at rolamite as a way of performing a lot of functions simultaneously. At Technar we have a facetious rule that says if you want to replace a specific function with rolamite, it turns out that rolamite is the second best way to do it. But in almost all cases where you want to do more than one thing it looks extremely promising. That is why I come back again and again to the idea that you do not want to build just a switch out of rolamite; you want to build something that incorporates a switch and something else, and something else, and something else. Then rolamite will come through."

N76-19454

APPLICATIONS WORKSHOP III-B-3

TRANSDUCERS AND MEASUREMENT

William P. Gruber, Technar Incorporated, Chairman
Workshop Consultants: F. A. Duimstra (SL)
and Reg Scroop (RTI)

SANDIA ACCELEROMETERS & VELOCIMETERS

ACCELEROMETERS

INTEGRATING DEVICES

Answering a question by Jim Means, Ordnance Fuze Laboratory, about devices which integrate acceleration to obtain velocity and displacement, Fred Duimstra replied, "At present Sandia has under development about five different devices. They range in g-levels from a low of about 5 g's up to about 20,000 g's. Some of the devices are purely g-level sensing devices. That is, they do no integration per se, but they simply sense a g-level and close a switch on achieving that g-level. The majority of them involve metering some fluid or providing damping by some other means. We can get either a single integration or double integration by the amount of damping and the type of return bias that we add to the system."

* * *

VELOCIMETERS

Duimstra went on to say that in the case of fluid-metering-type integrators, Sandia was interested in constant g-second product or velocity change. "If we are looking at a constant return spring force, we are still considering the first integral. We can change that characteristic by changing the return spring characteristic. None of these things are perfect integrators; they have to have some slope to them. You can change their characteristic by the amount of biasing built into the return spring."

* * *

BIASING

METERING AROUND ROLLERS

The common way of putting bias into the system is the cutout method--making notches in the band so as to give biasing forces in certain directions. Metering can be provided by the case when it is built with beveled internal corners. The bevels keep roller friction down by not allowing rubbing, but they also cut down the area in which gases or fluids can bypass the rollers when a liquid is pumped from one end of the case to the other. Fluid is pumped from end to end as the device is accelerated and the rollers begin to move.

It is important that the end clearance of the rollers be small, because these gaps do not have desirable characteristics as orifices. Slight shifts in the position of the rollers will cause large changes in the orifice characteristics and hence large changes in the g-t product.

BAND CUTOUT METERING

Duimstra then described two ways in which accurate metering can be obtained. The first technique (Figure 1) uses a band operating around a grooved roller. In this case, metering occurs through holes in the band at the point where the rollers are tangent.

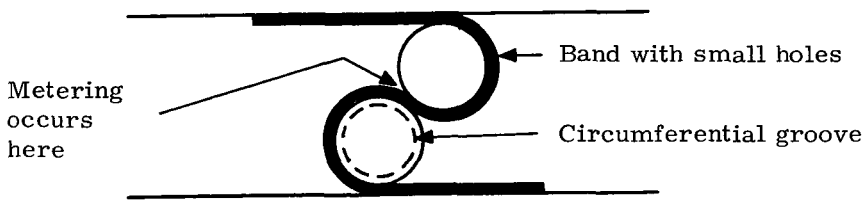


Figure 1

ORIFICE METERING

Another method employs modified guide surfaces as shown in Figure 2.

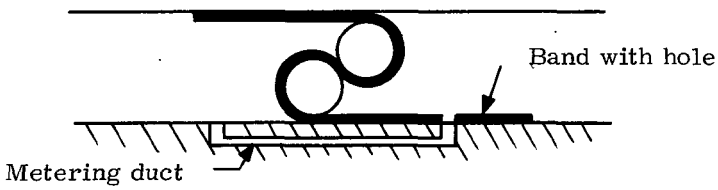


Figure 2

Both devices employ silicone fluids as the working medium; devices using these techniques operate to 20,000 g's.

* * *

REDUCING TEMPERATURE DEPENDENCE

Silicon oils have, of course, a viscosity temperature characteristic, which might make them ill-suited. What Sandia has done is to keep the fluid flowing in the turbulent state. If it once goes into a laminar-flow state, then its temperature-metering characteristic is quite nonlinear. If, however, the fluid flows through an orifice--usually a sharp-edged orifice will do it within a certain velocity range--one can obtain linearity over a large temperature range, as long as the flow is turbulent.

* * *

MAGNETIC DAMPING

William Gruber described a Technar timer which incorporates relatively large copper discs attached to the ends of one of the rollers. The discs turn between pairs of ceramic magnets to produce eddy-current damping.

VISCOELASTIC DAMPING

"Viscoelastic materials are also a possibility," Duimstra pointed out. "They can be sandwiched between metal bands to make a damped rolamite. One of the things I've heard mentioned for this is two-sided Scotch tape. This works fine until it's heated; then its characteristics change extremely. The approach is probably best suited to a one-shot device that doesn't have to work within a broad temperature range."

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Damping by introducing material in the band seemed not attractive to the participants for general use, however. As Duimstra went on to say, "If you tried to build a shock absorber for your car with viscoelastic material that is available today, I don't think you could do it. I don't think you'd get enough damping out of the material--even on a one-time basis--much less in view of these problems of damping versus temperature. If you want to absorb large amounts of energy, you are better off putting it in a fluid rather than a very thin layer."

* * *

BAND DEFORMATION DAMPING

As regards band damping, Don Wilkes pointed out that some titanium alloys are very good damping materials and still exhibit high structural life. Some of the alloys are exceedingly good energy absorbers.

A third possibility for damping in a device to operate up to 10,000 cycles was suggested--that of band deformation. The band might be stressed almost to its yield point and used in a channel which decreased in width along its length.

* * *

ZIPPER DAMPING

General Electric experiments with two pieces of stainless steel whisker material have shown that they can be peeled apart an infinite number of times with substantially the same force. The material can be made in different peel strengths and would seem to be less temperature-dependent than any of the other techniques for rolamite damping.

One participant, using material available commercially from Velcro, had attached the zipper material to stainless steel sheets of honeycomb. Welded to three or four mils of the parent material, it lasted thousands of hours at high temperature.

* * *

INHERENT DAMPING

Don Wilkes pointed out that something like zipper-type damping "is exhibited by the bands, and one finds this radial asperity which occurs in the finest rolamites. We have been able to separate the friction components, and one of them is a thing very analogous to what you are talking about on a microscale. As the band and roller come together, you have a sort of radial sliding. We know it is not a circumferential thing, but it is this phenomenon that allows it to improve with repeated traversals."

* * *

TRANSDUCER MEASUREMENT AT LOW PRESSURES

Mr. McClendon expressed an interest in rolamite for pressure transducers--differential and absolute--for measurement of pressures down to 0.05 psi. "Our devices exert very small forces," he said. "Anything to which we couple causes hysteresis. How does rolamite compare on this problem inherent in conventional motion transduction systems?"

FRICTION LOSSES

Duimstra's measurement of rolamite friction losses, where most of the problem occurs, found 0.0002 to about 0.0005 for a coefficient of friction. This was over a limited loading on the rollers and guideways.

* * *

MOTION APPLICATION

Duimstra suggested that for small McClendon's forces, a simple motion-amplifying device can be made using a stepped roller with an attached tongue (Figure 3).

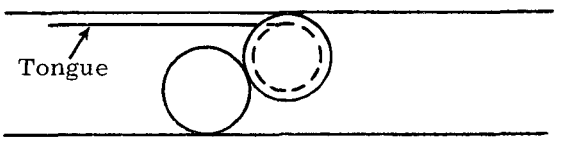

Figure 3

When the tongue is moved a small distance to the left, the rollers move a much larger distance to the left if the difference in the two diameters of the upper roller is small.

* * *

SIMILARITY TO FLOW METERS

With g-second devices--integrators--Sandia measures the consistency of g times time over a large g-range. Duimstra pointed out, "I suppose you could reverse the process and make it a flow meter. Of course, I think you would be limited in the types of fluid you could use. We haven't had an application along that line, but I don't see any reason why it wouldn't work."

* * *

READOUT

Duimstra described how readout can be accomplished with a spring-loaded blade which is released when the rollers have completed their integration (Figure 4).

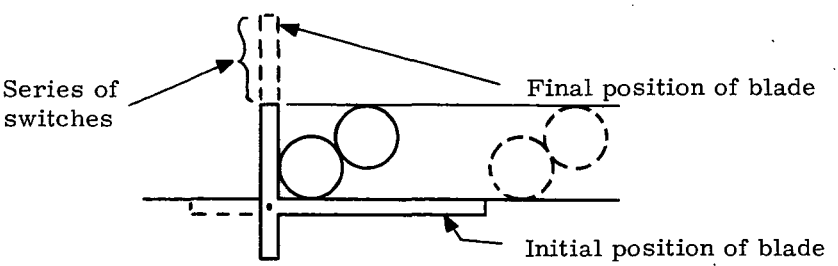

Figure 4

This system permits many contacts in a small device and gives good contact separation and voltage holdoff. Sometimes the readout is mechanical--the cluster releases an auxiliary spring which fires a percussion cap or similar device.

SLIPPING

Reports concerning rolamite say that no slipping occurs of the rollers with respect to the band. Some workshop discussion centered on the question of microslip in motions of hundreds or thousands of times. The best answer to preventing slipping is to attach the band to the rollers by some mechanical means. A reasonable amount of band tension will prevent creep, but for critical high-accuracy applications, some research on microslip is needed. Sandia is beginning some work in the area.

* * *

FRICTIONAL LOSSES IN SIDE LOADING

Few data exist for friction measurement under sustained side loads. If the loads are in a direction counter to the restraint of the rolamite bands, it is likely to add to the friction. The rolamite suspension doesn't prevent motion to the side of its own accord. It has some stability in that direction, but not enough for sustained side loads. Within relatively narrow limits, Duimstra felt that the suspension system itself is as free from friction as a lever system might be.

* * *

SIDE LOADS IN ROLAMITE

CONSTRUCTION TO CONTROL SIDE MOTION

Creep under side loading depends on the perfection of the cylinders and guide surfaces, Wilkes pointed out. "If the guide surfaces are tilted or if the rollers are tapered, they will tend to tear apart. We like rectangular channels--tubes are the best. If you make a channel with support on only one side, there will be normal forces to spring it apart, and that is the very worst thing that can happen to a rolamite. I like to use tubular construction where the guide surfaces are supported symmetrically on both sides.

"The only way to combat side motion is to use rails and force the rollers to move in a straight line. Of course, if you are talking about limited travel, the rollers and band can be pinned together and you'll never have any problems. Extremely large widths can give very good directional control, but in normal proportions you must control the direction by some mechanical means."

* * *

MISMATCH AFTER CYCLING

In response to a question on data about mismatch between band and roller after cycling, Wilkes described an experiment in which he ran a thousand cycles and had been unable to measure 0.0001 inch variation.

* * *

ALIGNMENT WITH CROWNED ROLLERS

In response to a query about using crowned rollers to force alignment, Wilkes replied that a stress situation of reverse flexure was accentuated by crowning. An inherent instability results, and the rollers do not stay on center.

CONCAVE ROLLERS

"We do use concave rollers," Wilkes said. "And I have used rollers that nest with pretty good results. But if the purpose of the whole thing is to keep the band in place--it's not advisable. I have tried crowned rollers repeatedly, with very poor results. If you want a recirculating geometry, you cannot rely on brute force accuracy. A successful rotary rolamite must have the ability to slide. Maybe it is only a small effect, but it must have the ability to right itself occasionally."

CONCAVE-CONVEX COMBINATION

Making one roller very slightly concave and the other very slightly convex seems of questionable value, since the band just bridges the concave roller.

* * *

ROUGHENING

The workshop also considered the alternative of using band material with an imperfect surface or longitudinal grain. Improvement in alignment characteristics would have to be measured against friction loss, however. RTI's tests with alumina ceramic rollers showed that the coefficient of friction went to three times its value at most levels.

* * *

STRAIN PUMP OPERATION

Don Wilkes described work with a rolamite device subjected to varying acceleration, with different tensions in the two bands--in effect, a strain pump. "If you move the cluster back and forth you will have a redistribution of tension. This is a small effect, but you can measure it with strain gages. I am interested because it is the ideal mechanism for making motions as small as a millionth of an inch or so, in a repeatable way," Wilkes said. "If you put a certain differential tension into the band, you pump that much strain through the cluster if you make a traversal; you can really control very small motions. You have a dynamic situation also--that is, you cannot transmit a torque unless you have differences in tension. As far as the static situation goes, there need't be any sliding at all, but if you move it you will have a difference occurring in the two bands in any very dynamic situation."

* * *

TESTING

RTI has run separate tests on the device, and intends now to apply the actuating accelerations at the same time as the vibrational g's. They have built devices that have survived vibration in the range of 20 to 2000, to 20 cycling vibrations, up to about 5 g's amplitude for about three hours in the three axes.

N76-19455

APPLICATIONS WORKSHOP III-B-4

MANUFACTURING PROCESSES

B. S. Gardiner, Sandia Laboratories, Chairman
Workshop Consultants: G. R. Elliott (SL);
Gerald Zimmerman (Hamilton);
J. P. Myers (SL); W. D. Jones (SL); E. D. Roth (SL)

B. S. Gardiner began the workshop with the following presentation, describing Sandia's shop techniques.

SANDIA PROCESS FOR MAKING PRECISION ROLAMITE

The Sandia shop is primarily responsible for the fabrication of bands, fabrication of contacts or any part that would have to be etched, and the assembly of all parts, as well as the directing of the fabrication for such parts as rollers and cases. We put orders on other shops, and follow the proper inspection. We make complete assemblies. Then we test the units through all environments on test equipment we designed.

* * *

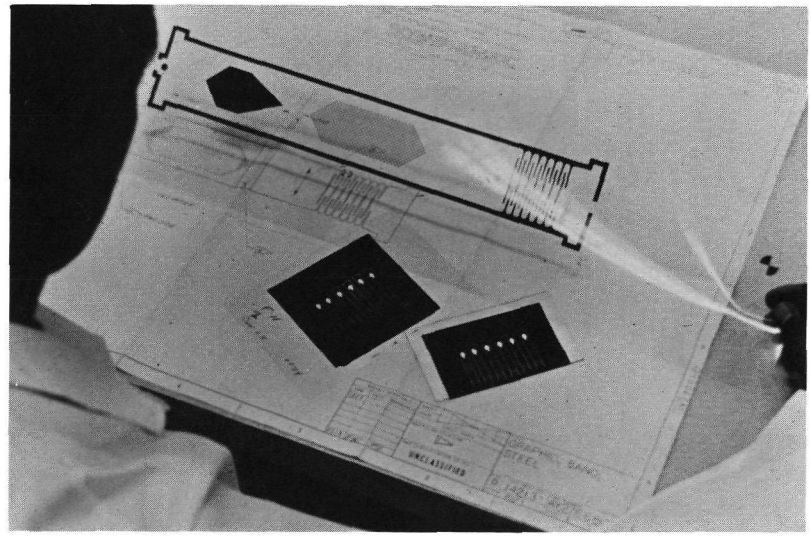

Figure 1. The Gerber Plotter, 10-to-1 Master

PHOTOMASTER

The plotter is on 7-mil Mylar, a 10-to-1 of the first band used. I'll refer to this as the MC2471, a 5G rolamite. The smaller multiple is a Mylar multiple; the one on the right is glass. We are going more to the glass; we can get more stability and have fewer problems with heat.

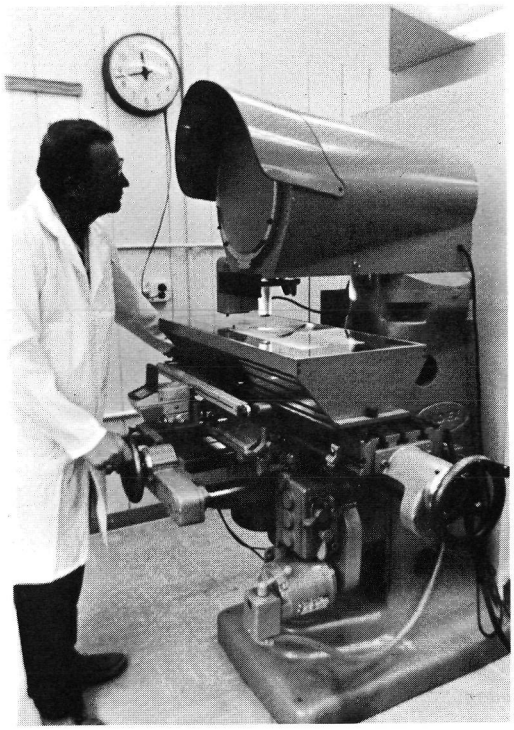

Figure 2. A Converted Index Mill Base Optical Comparator

A converted index mill base gives us a travel range of about 24 by 12 inches, so that we can accurately analyze the condition of the master before having photo reduction. All measurements are on direct reading instruments with the possibility of error quite low. We hold our 10-to-1 masters to within 1 mil and we reduce down to 1/10 mil, holding all tolerances in all directions to 1/10 mil. Because we go from the Gerber plotter to a photo reduction system we will have a little accumulated error, but we are within 2/10 of a mil on our final negative that we will be using for processing.

* * *

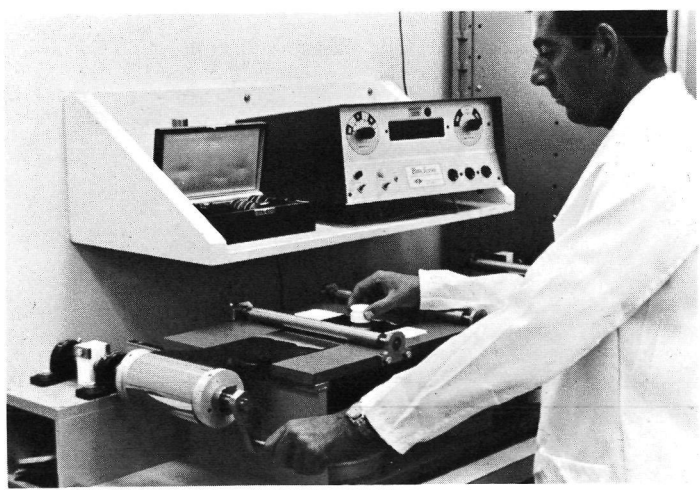

Figure 3. Betascope

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We start off by measuring the materials that we are going to use. In this case, because we are generally less than 2 mils in thickness, we use the Betascope. The Betascope is better in the low thickness measurement ranges. To get above the few mil range you must go to X-ray or direct mechanical measurements. We will be able to get down to a few millionths of an inch accuracy measurements. We can crank rolls of material through this table.

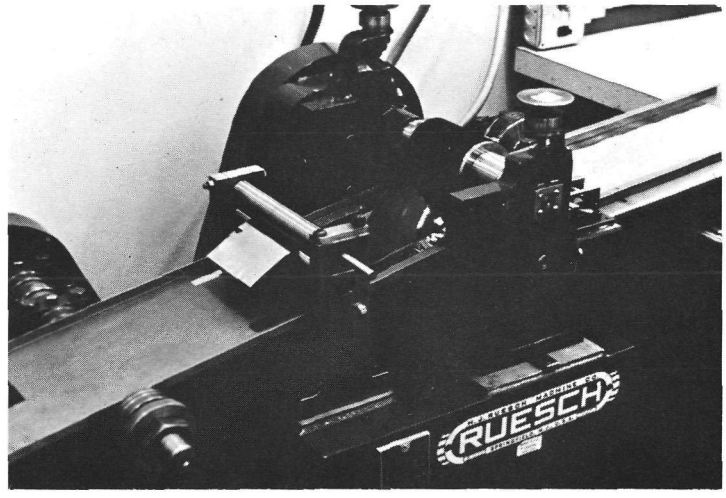

Figure 4.
Slitter

BAND MATERIAL PROCESSING

The slitter is used to cut the width of material for laminating. It is rare that we would use the slitter for separation of bands from the multiple etching pattern. It is used for getting a good, true, accurate edge for laying up laminates. We have slit materials as thin as 3/10 of a mil in stainless. We have to back up thin materials with paper or some other material. We can go up to 10 mils in thickness on this piece of equipment and hold the width accuracy to 2/10 mil.

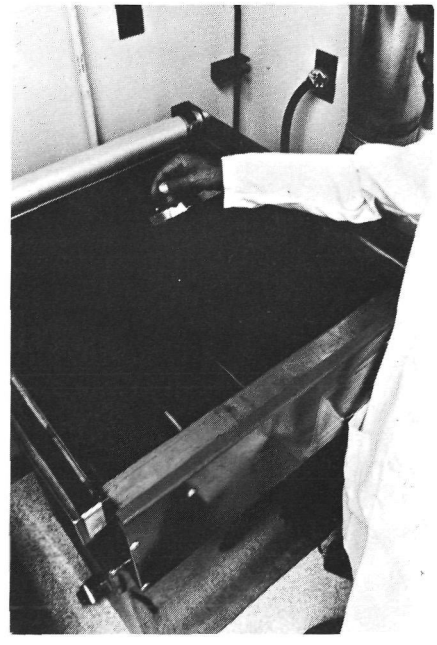

Figure 5.
Vapor Degreaser

We must make sure the material is thoroughly clean; vapor degreasing is one of the methods; we also use ultrasonic cleaners.

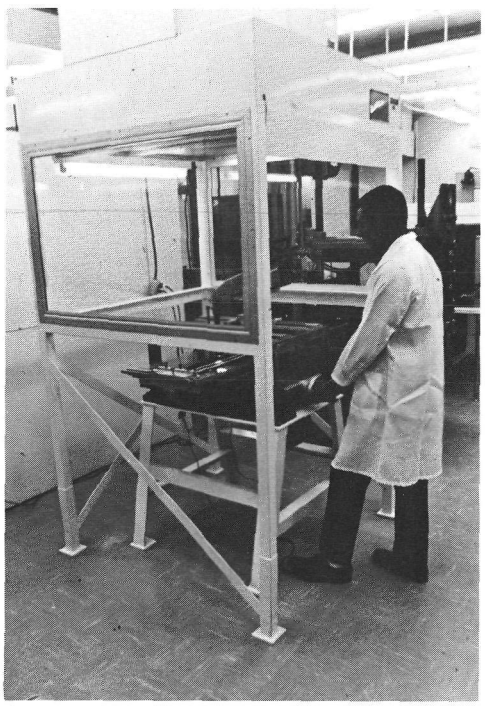

Figure 6. Laminant Lay-Up Table, View A

We use a laminar down-flow cage to make sure the dust and dirt particles are kept off the laminants while we are laying them up.

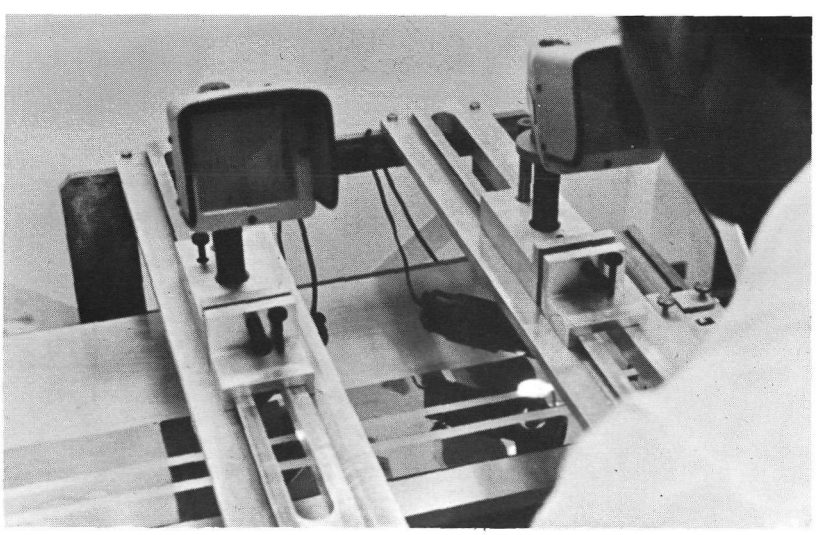

Figure 7. Laminant Lay-Up Table, View B

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Figure 7 shows a better view of what we are trying to do. We have, in this case, 5-mil beryllium copper with 2-mil adhesive Mylar, and on top of it we have 1-mil beryllium copper. Two optic systems are used to reduce the amount of travel to cross the table. The two optic systems will normally be lined up with each other.

Figure 8. Press

Once we have the materials laid up as we need them on the laminant lay-up table, we can remove the whole table top, put a cover plate over it without removing the material from that table top, and insert the top into the press. The press is capable of about 15 tons on a 6-inch ram. We can heat the platens to a temperature of 600 degrees for any time that we desire, so that we can properly make a good, secure laminant.

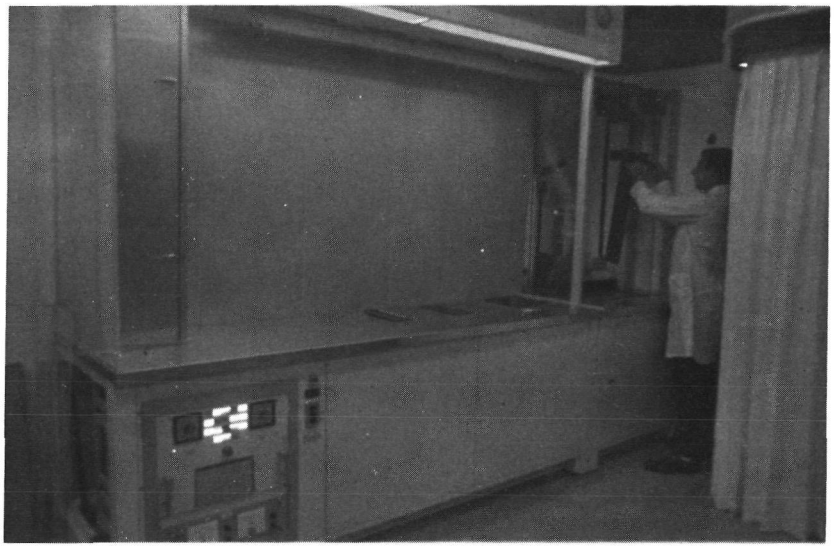

Figure 9. Exposure and Cleaning Area

PHOTO ETCHING

This is the yellow light area, where we do the exposing of the resist-coated materials and where we clean the materials and develop the exposed pattern. A laminar outflow bench is conveyerized and is driven by the control panel. By programming the drum properly we do scrubbing, rinsing, and resisting operations in very controlled conditions at very controlled rates. We went to a vertical resisting method, and a vertical scrubbing method, to conserve space. For horizontal systems we need much larger facilities. The right-hand tank where the conveyer system is being loaded is a detergent abrasive wheel scrubber tank. The next tank is a rinse tank, using tap water as a rinse and soft brushes for removing the detergents. The next three tanks can contain any combination of solutions. We use a couple of deionized water rinses and a light nitric acid solution followed by a final deionized water rinse. The open tank in the middle is an oven. We can get up to about 300°F to dry the materials before resist-coating, and to cure the resist after we have resist-coated. The small tank, to the left, is the resist. We use a positive resist. We extract at a controlled rate to get a uniform thickness of the resist on the material. After we have resist-coated, we move over to the oven and bake for 15 minutes to make sure that the resist is dried. We have thought about speeding up the drying time of the resist with infrared light.

Here we use the multiple negative method of exposing the resist-coated material. We can expose from either side with this system. We have found that the exposure times are approximately 1 minute and 15 seconds. The thickness of the resist is about 1/10 mil.

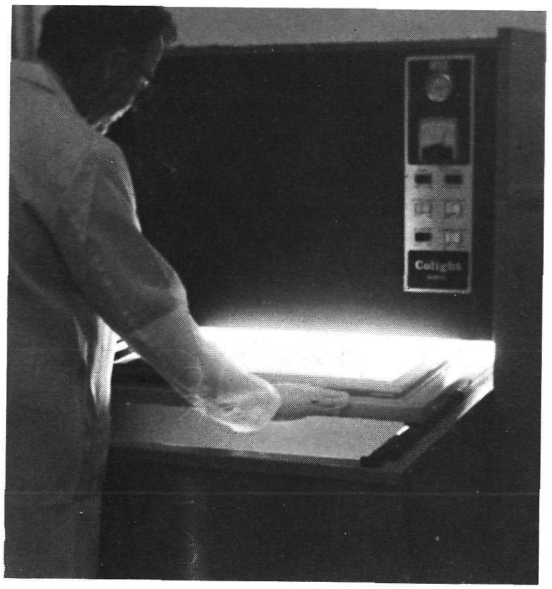

Figure 10. Colite Mercury Lamp Exposure System

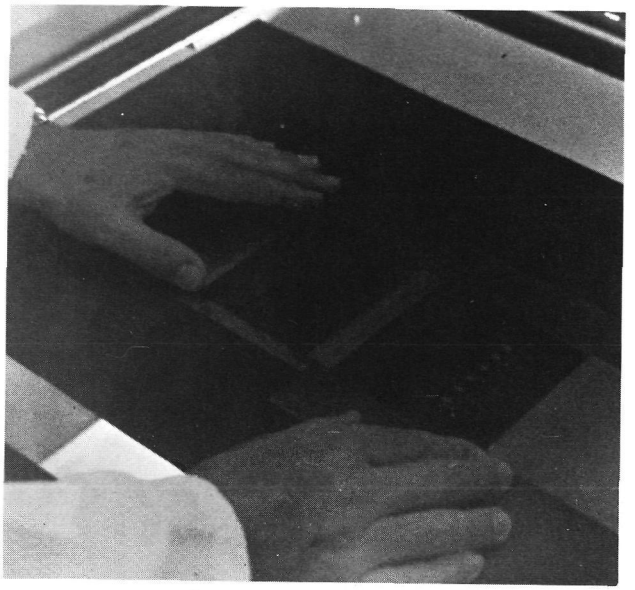

Figure 11. Close-Up of Colite System

Figure 12. Step-and-Repeat Exposure Table

The table itself is moved by an air motor drive, with a detent rack underneath the table. There are two exposure heads, one above and one below the table. The heads are air-cooled. There is a 750-watt mercury lamp in the top of each head. The small hoses on the right are for holding negatives very closely to the material so that we do not have any flare from the negatives' separation. The two instruments at the upper

left are densitometers. They will accurately control the amount of exposure on each band. One advantage of this system is that we can detent and we can register. We can always go back to a given spot and re-expose if we have to, as in the case of laminants. We may have to expose several times. We are using, in this case, not the multiple negative but a single negative that is extremely accurate--one that we select from a batch of negatives and one that we know is accurate.

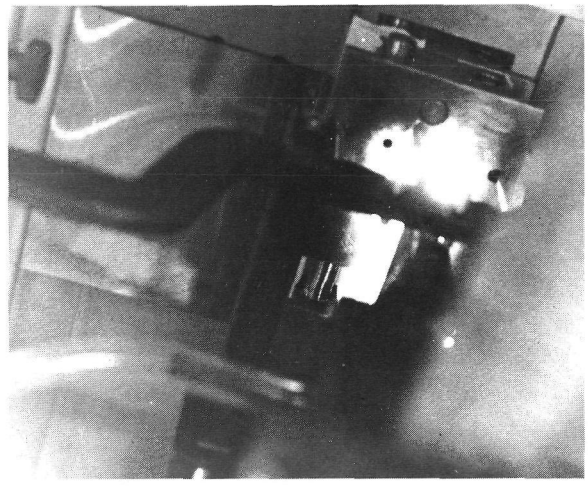

Figure 13. Location of Negative in System

We can reproduce bands very accurately without selecting one out of a batch. The system is very repeatable. In the case of the MC2471 band of 1-mil-thick stainless, we are asked to hold 1/2 mil on the length and 1/2 mil on the force cutout.

Figure 14. Spray Developing the Positive Resist

We hang the material in the tank, which is about 3 feet deep, and get a good spray-and-wash action.

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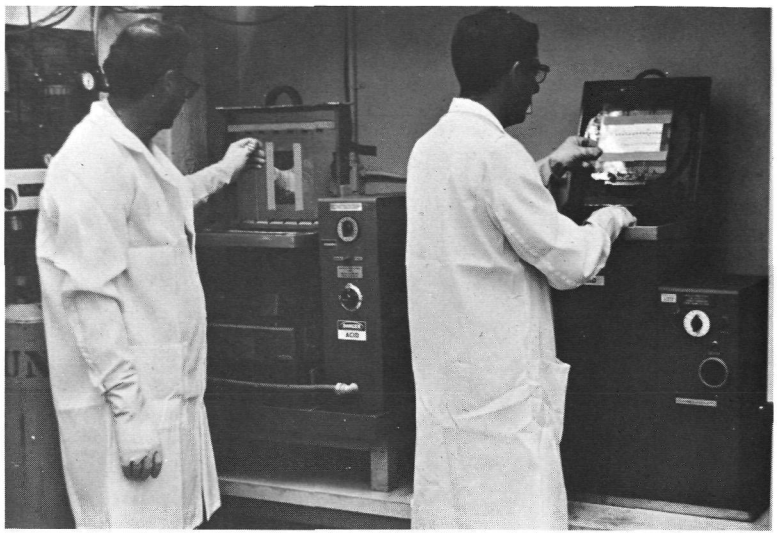

Figure 15. Etching Room

These two small etchers are used for developing the processes. The revolving etcher on the right holds the work horizontally. The spray is vertical in the bottom of the tank. The etcher on the left is vertical work with spray-etching from the front or back. For single-sided etchings we put a plastic plate in the frame.

Figure 16. Large Etchers

The larger etchers prove the ability of the system to produce. Once we devise the process for etching we are going to the big etchers and come out with methods that are suitable for production of any quantity of rolamite bands. In this case we have to support the material in a frame. We may have to go to the basket but now we use the frame of Fiberglas phenolic to support the long strips of material that run through the etching tanks. They come out on the right side completely rinsed.

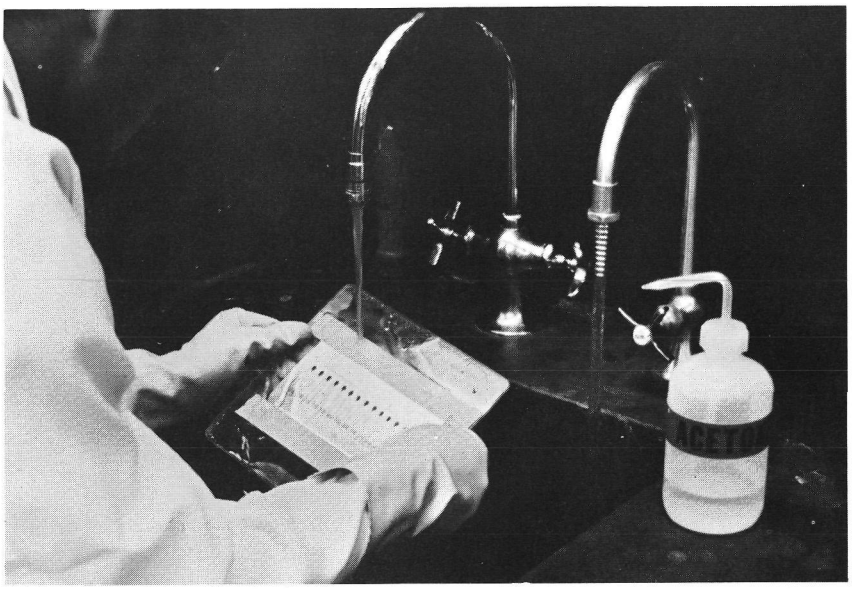

Figure 17. Removing the Resist

We wash off the remaining etching solution and then strip the resist with acetone. It is a very clean process--perhaps a little bit cleaner than the negative process that many of the printed-circuit shops are using.

* * *

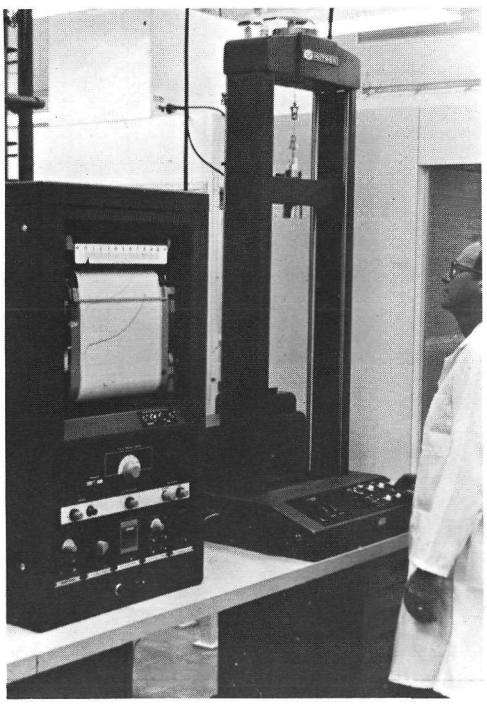

Figure 18. Instron Machine

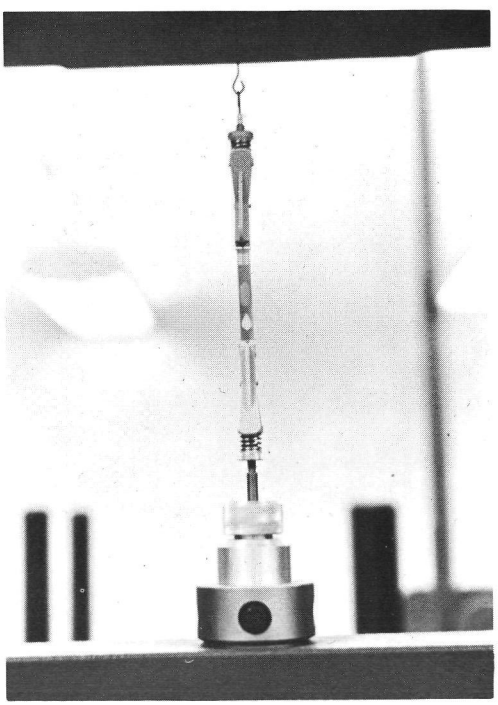

Figure 19. Close-Up of Tested Band

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BAND PROPERTIES -- MEASUREMENT

The Instron machine was used to a large extent in developing some of the technical data presented yesterday. Here we show a rolamite band. The rolamite band is suspended between the jaws of the Instron machine. We are actually stretching the band. We have an etched spring portion in the band. The top portion is an etched spring pattern. This spring holds the rollers in the proper geometry in a rolamite assembly, and we are measuring the force in that spring. We have an 18-gram deflection with about a 0.050-inch pull on the band itself. We will be able to measure the friction we have left in the systems.

* * *

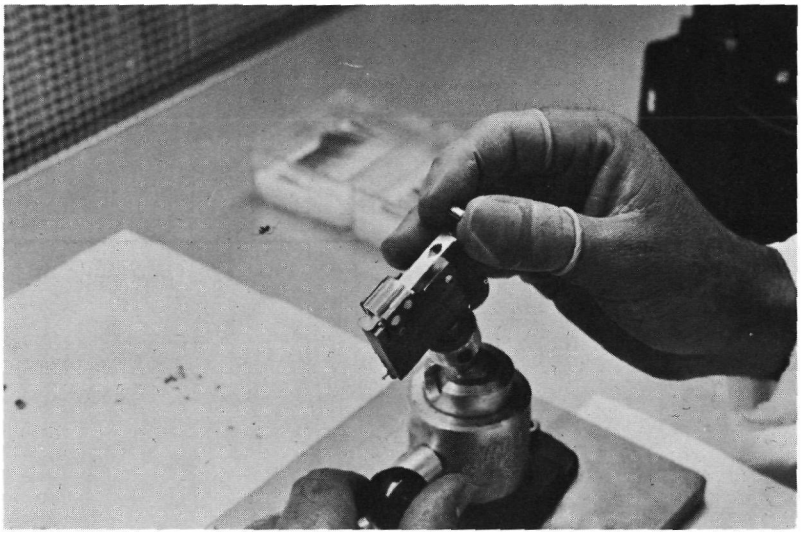


Figure 20. Assembly of the MC2471

ASSEMBLY

The parts are caps and extra bands and contacts. We are using a "third hand" assembly fixture. The rollers have a tendency to fly out. We use the "third hand" fixturing to avoid that problem. All our assembly is done on the laminar flow bench to keep the system as clean as possible.

* * *

FINISHED DEVICE

Figure 21 shows the triangular force cutout in the top of the case. The rollers are stainless steel, the end caps are made of polysulfone, and the case is glass. The cylindrical glass is shrunk around a tungsten mandrel to get the correct configuration holding the proper ramp angles in the corner and proper dimensions across all parts of the case. We have used glass for cases quite extensively.

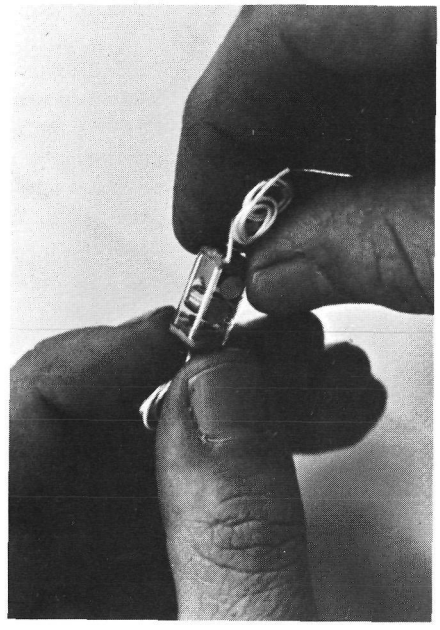


Figure 21.
Finished MC2471

* * *

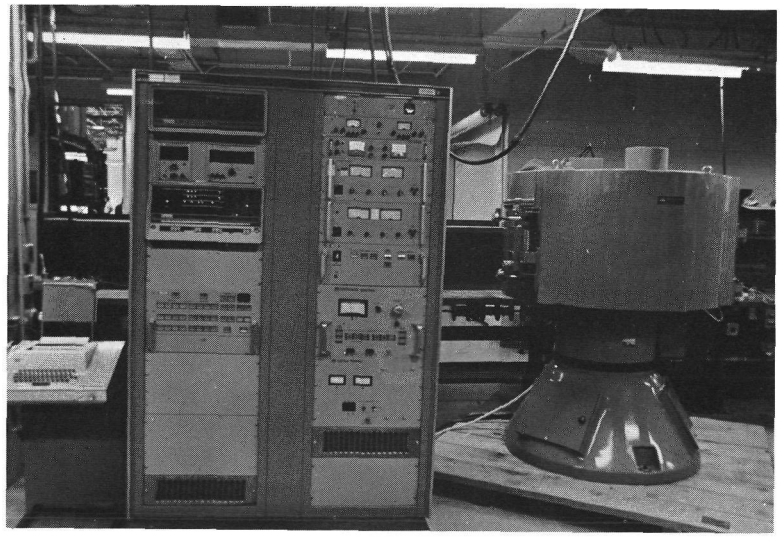


Figure 22. Test Equipment Designed by Glenn Elliott

DEVICE TESTING

The teletype input computer is a digital PBP-8. The system on the left is the main frame. On the right is the manual control of the centrifuge and centrifuge controlled mechanism.

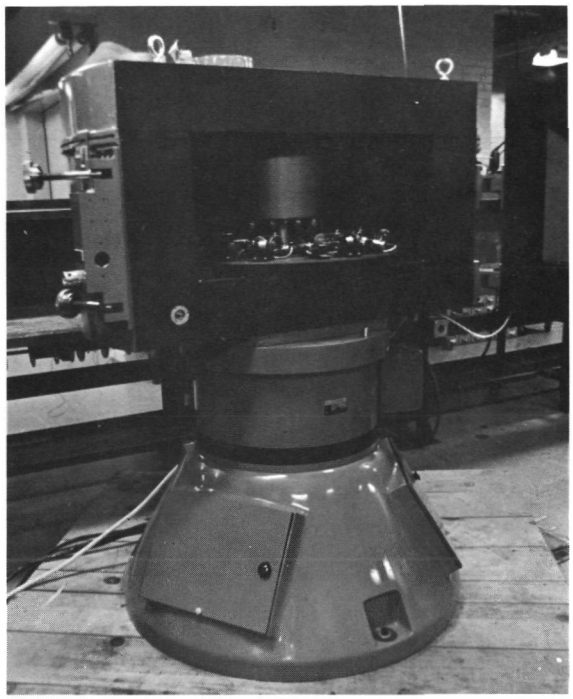


Figure 23.
Test Centrifuge

The centrifuge in Figure 23 shows the fixture for holding the MC2471 during test. The table has eight stations plus two setting stations.

Figure 24.
Close-Up of
Fixture

The flexible drive mechanism allows us to rotate the fixture 180 degrees for the reset position or the actuate position.

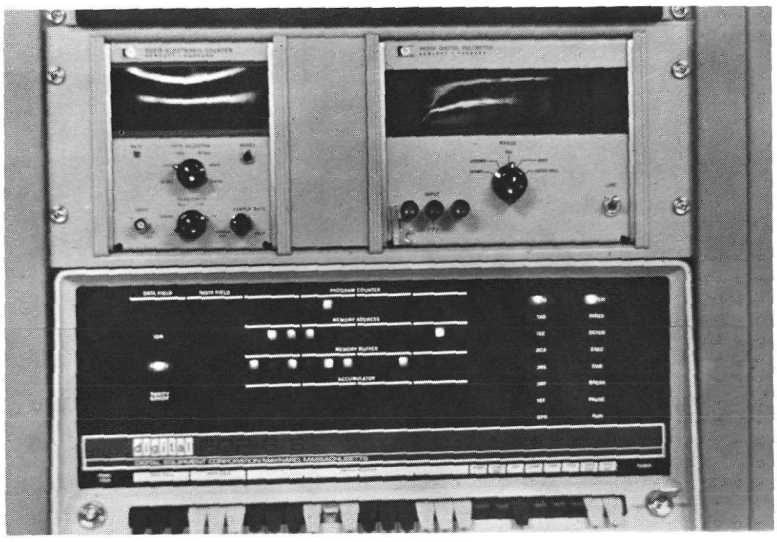


Figure 25. PDP-8/S Computer

The upper equipment is used for measuring contact resistance, g levels, and hi-pot values.

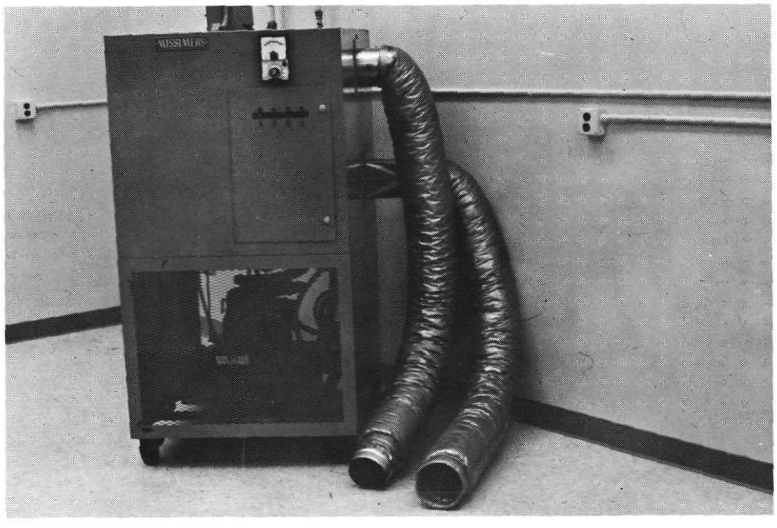


Figure 26. Environmental Cycling Chamber

This chamber allows us to go from a minus 100 to a plus 500 degrees F within the centrifuge chamber itself. It is independently operated.

We also use two thermal shock chambers. One is set at high level, the other at low level, and we transfer the material from one chamber to the other for thermal shock and then go back to the test equipment and test again. Other shock tests and vibration tests are run on the units, but other organizations are responsible for that type of testing.

PROPERTY MEASUREMENTS

Discussion in the workshop began with the problem of measuring extremely small tolerances in sealed assemblies.

E. D. Roth described Sandia techniques:

"Building cases out of four pieces is better than attempting to inspect a one-piece case before assembly occurs. We have found that by using a grazing incidence interferometer we can turn the usual microferometer into a macro-interferometer, and by using a grazing incidence angle of about 5-3/4 degrees and looking down one wall of the case we can get fringe separation using mercury lights that are about a hundred millionths apart. If we have an angle that perhaps is 400 millionths high, 15 mils wide down the side of the case, we will have those four fringes bent around the side; you count the fringes across and know the height of the angle.

"Another way of inspecting is to modify a Clevite gage, which can be done. You can put a tilt tip on the end of the gage and actually go right into the corner within 1/2 mil of the corner of the case."

* * *

FINISHED DEVICES FOR HIGH PRESSURE

A participant whose application required high pressure inside the rolamite inquired about methods for holding the ends of the bands and sealing the case. In Sandia's development of the MC2471, the ends of the bands are tabbed to hook over the ends of the case. The end cap is sealed to the glass and the band with a silastic material. With variation of temperature the problem is more complex--the epoxy must expand and contract uniformly with the case, whether it be glass or whatever. Most of the hard epoxies have a different coefficient than glass. The first Sandia models had a rigid epoxy in the cases under different environments. In vibrations especially, the cases cracked, since there was no give between the polyurethane ends and the glass. Going to silastic has created some other problems--it is not rigid enough.

EPOXIES FOR SEALING CASES

The sealing problem is complicated even further when electrical contacts are required.

* * *

TOLERANCE PRODUCTION OF CASES

Sandia arrived at four-piece case construction because of requirements for stainless-steel cases that were a few tenths in geometry. Making the cases out of four pieces allows preinspection of each piece before they are put together. This device fits on a surface plate with jaws perpendicular to the surface plate within 50 millionths. The case is assembled over a mandrel which can be adjusted in size. The four-piece case can be epoxied, soldered or welded. However, Sandia finds it very difficult to make a confidence-type inspection for pressure.

* * *

CASE PRODUCTION--TOLERANCES AND COST

At this juncture, W. D. Jones addressed the following remarks to the workshop in general:

"It is evident that Sandia is working with very, very close tolerances. We are spending a great deal of engineering time and production time and money to work to 1/10 percent in the cases, and I think it is important--especially if you are in a nonmilitary, commercial endeavor--that this degree of high precision does not deter you in your creative efforts of finding application for rolamites. The cost of making them is naturally important. With sufficient creativity on your part you will find, in most instances, economical applications of the rolamite principle. Take the case manufacture as an example; of necessity, we have had to work with the most exotic and expensive manufacturing processes. We have worked with electroform. It takes about 24 hours to form a case which would be equivalent to what we have assembled here in stainless steel, and it wouldn't be stainless steel--it would be nickel, which is hard to machine. Here it would be expensive without a doubt. How many of these cases we can get off of a given mandrel when we are electroforming them is problematic. Frankly, at this point, we would be lucky to get as many as 10 cases off of a mandrel before we would have to scrap it out. Mandrels may cost anywhere from $100 to $200 apiece.

ELECTROFORM CASES

One case per 24 hours is out of the question. The glass cases are made by vacuum shrinking under heat around tubular pieces over graphite-coated mandrels. If it is a complex shape it may take as many as five preforms. The simplest thing to vacuum-form would be a circle. The next simplest would be an oval, and then we get down to squares and non-square rectangles; if you have multirectangles you are taking perhaps 2-1/2 or 3 hours just to make the case, and then there is inspection time. Once you have your broaching machine, the broaching could be done for pennies in high production, and you could probably hold safely to plus or minus 1000, maybe a little less. But on the type of configurations we are talking about, probably plus or minus 1000 would be a practical tolerance in the broach chain. You may not even have to broach. You could buy commercial drum brass tubing either to size or design the product so that you merely run a sizing mandrel through the blanks and cut, baloney fashion, from your commercial brass tubing. Extruded cases can be automated so that actually you hardly touch the cases--with tubing and baloney style cutting each gets sized and comes out a complete case, plus or minus 1/1000 of an inch. The point I am trying to get at is this--I know that the rolamite units can be made for very competitive costs, can compete very well. "As for commercial hardware, rollers can be made for virtually nothing on screw machines; bands can be made in lattices 100 or 200 at a time by chemical milling."

GLASS CASES

BROACHED CASES

EXTRUDED CASES

* * *

HIGH QUALITY LOW COST ROLLERS

J. P. Myers added to the discussion of commercial casting of rolamite hardware, "I feel you might be able to make six rollers out of a $1.50 gage pin all the same size. I think that would be perhaps a better approach. Let's assume, to begin with, that we need a 3-to-5 microinch finish on the OD of rollers and we need roundness within millionths and we need a tolerance of 10ths of a mil. If you don't need quite as good a finish, if you can stand a little out-of-roundness and so forth, you can get centerless lap stock within plus or minus 2 or 3/10ths, as you know. Centerless ground stock within plus or minus 1/2 thousandths is no problem.

PRODUCTION TOLERANCES, CASES

Myers went on, "Perhaps Sandia, in a desire to get super-accuracy, superreliability in components, may overdesign a lot of things that we do. In the testing experience that I have, I have one rolamite unit (keep in mind that this is the device with the Pyrex glass case which we have tested for about three months in proving out our test equipment) where this case is actually broken or cracked right down the middle. It has a thermal crack in it and this device exhibits extraordinary repeatability and reliability. I have never seen it fail, I have never seen it differ outside the tolerance rating on the g closure of about 0.05 g, so it is 1 percent accurate and it is reliable. I bring the point up because perhaps we don't need these accurate cases.

"I think this is true and on commercial devices especially. The tolerances don't have to be held--except when you start considering pumpers, either gas or liquid, then tolerances do get to be a problem. If you don't need the tolerances, don't use them. Get good repeatability--that is a good point. The mandrel material may be plastic; so far it has worked pretty well in the experiments that have been conducted. If the tolerances are liberal enough, you could use the melt-away or throw-away type of electroforming mandrels; that is what we are talking about here. Make them out of plastic and coat them with silver or something to go on the plate; melt or push out the plastic, throw it away."

COMMERCIAL PRODUCTION

A general discussion of rolamite's commercial potential reached beyond its use as laboratory technology. Used for subcomponents of commercial products, the whole rolamite assembly would cost cents to a dollar. Since one of rolamite's attractive features is that it can generate forces and operate with less than perfect manufacture, participants were interested in using fairly rough rollers, extruded cases, and bands that would be cut off on a slitting machine. One manufacturer said, "I am convinced when we are talking tens of thousands of units in production, that rolamite units could be made as a type of device for less than a dollar apiece."

OPERATING CHARACTERISTICS AT HIGH TOLERANCES

However, discussion did point out that much compromise for commercial production could introduce higher side loads. Tolerances must also be maintained for high numbers of cycles of operation.

RELIABILITY OF LOW-COST UNITS

Rolamite is not unique insofar as manufacturing processes are concerned. All design considerations should be brought into the choice, whether it is rolamite or something else; it will take its place among the available routes of design just like anything else.

In a question directed to John Ford, a participant asked, "Could very low-cost units be built, in your experience, so that we could still expect reliabilities as high as 95 percent? Could we put these up in a parallel series combination to achieve an over-all reliability?"

Mr. Ford replied, "I think rolamite is adaptable to very cheap manufacturing techniques as long as you don't have to have very close tolerances of the band. I think there are ways of making the case and rollers cheaply. I would say that in all probability you could make the rolamite device cheaply for high reliability.

* * *

ASSEMBLY

The workshop recognized that a man in the field cannot easily replace a band or part of a unit. The time involved in removing the silastic and reconditioning the system for reassembly is too high. Destroying the unit completely and going to a new one is not unique to rolamite devices.

There are ways of designing the band to be extremely simple to put in commercial devices.

BAND PREPARATION FOR ASSEMBLY

In the second generation MC2472, Sandia has been stiffening the ears on the band. They are using 7-mil-thick stainless steel, about 60/1000 wide, that will be bonded to the 1-mil beryllium copper band material, specifically to stiffen the end tabs. To line up the ears so that they are exactly 90 degrees, they created a simple fixture that will match up the materials; then we put the band in a press, heat it up, and let it set. The laminant lay-up table was not suitable because this material has a tendency to "walk."

BONDING

Sandia reported good shear retention, and good shear bond between the stainless and beryllium copper with BR-1000, but it peels off very easily. This may cause us to resort to spot-welding.

ETCHING BONDED MATERIALS

Bonding does not affect etching, because ammonium persulfate does not attack the stainless. Beryllium copper can be etched as necessary, and the stainless steel then sheared off.

ETCHING A TAB FOR HOLDING BAND TENSION

To hold tension in the band, Sandia described a scheme of etching a tab out of the band. This tab will move out over the roller and will actually attach to a coil spring to keep the system under tension and in the right geometry. In the case of a first rolamite with the stainless steel band, there was an etched spring in the band itself. In the second, it is a coil spring pulled out around a minor diameter in the roller and attached to the end cap with the precision coil spring. A reduced diameter with the tab is needed primarily for clearance. If the tab is broken out, around the minor diameter, tension can be kept on the system without any interference problems. The coil spring was used because differentials in forces made such a design preferable to having it etched out in the spring system.

To avoid a tear problem in this design, Sandia is coating the tab area of the band with about 1/2-mil nickel, and etching through from the back side. Nickel over a wide area will strengthen the tab junction and keep it from tearing out.

N76-19456

APPLICATIONS WORKSHOP III-B-5

THEORY AND FORCE GENERATION

Dr. Lon E. Bell, Technar, Inc., Chairman
Workshop Consultants: C. Mark Percival (SL); Dean Gladow (RTI); and F. R. Norwood (SL)

COEFFICIENT OF FRICTION AS A DESIGN CRITERION

Chairman Bell began the workshop session by clarifying his remarks on coefficient of friction made at the first day's meeting. "I would like to put into perspective what I meant by my remarks yesterday on the coefficient of friction. There are two classes of rolamite devices. In one, rolamite is used in a system with an external load on the rolamite. One of the rollers has an extension, and a table, or the like, rides on the roller. As the table and roller cluster move back and forth, there will be friction. The question becomes, what is the ultimate coefficient of friction of the system? That is, how hard do you have to push on the table (compared to the table weight) to make it move? Therefore, we are interested in the ratio of the load to the force required to move the load; or the coefficient of friction of the system.

"In the second class of rolamites--devices that are not suspension systems, but complete within themselves, such as rolamite switches or pressure transducers--all we ultimately care about is how freely the cluster moves back and forth. That is the criterion that is going to be tied to design specifications.

Naturally, to design the device to meet specifications, we do care what the coefficient of friction is, but what we ultimately care about is the resultant freedom of motion. The mere fact that the rolling friction is small may or may not make rolamite attractive in particular cases where free motion is required."

* * *

EFFECTS OF NON-PARALLEL GUIDES

The effects of nonparallel guide surfaces on angle of repose interested James Means. Percival pointed out that, if the channel undulates or varies in cross section, the angle of repose changes, and so the band length needed to keep the geometry at a certain tightness also changes. There are two cases: (1) a loose geometry where the band just flexes, and (2) a tight geometry that either binds the cluster, or, if slippage and relative motion are allowed, where a combination of sliding and rolling can occur as the cluster moves through the channel.

Also, when the angle of repose changes, the normal force changes. Theoretically, the normal force becomes infinite as the angle of repose approaches 90 degrees.

* * *

ANGLE OF REPOSE

Gladow remarked on the extreme importance of the angle of repose. Two limiting conditions exist: first, where the rollers very nearly fill the channel; and, second, where they are very nearly on top of each other (Figure 1). The angle of repose is defined as the angle between the centerlines which, of course, goes from very nearly zero to very nearly 90 degrees. The basic formula (the "F equals MA" of rolamite design) is TS = NA. T is the band tension, S the guide surface separation, A the distance between roller centerlines, and N the normal force the rollers exert on the guide surfaces. Naturally, the angle of repose, θ, can be written in terms of S and A.

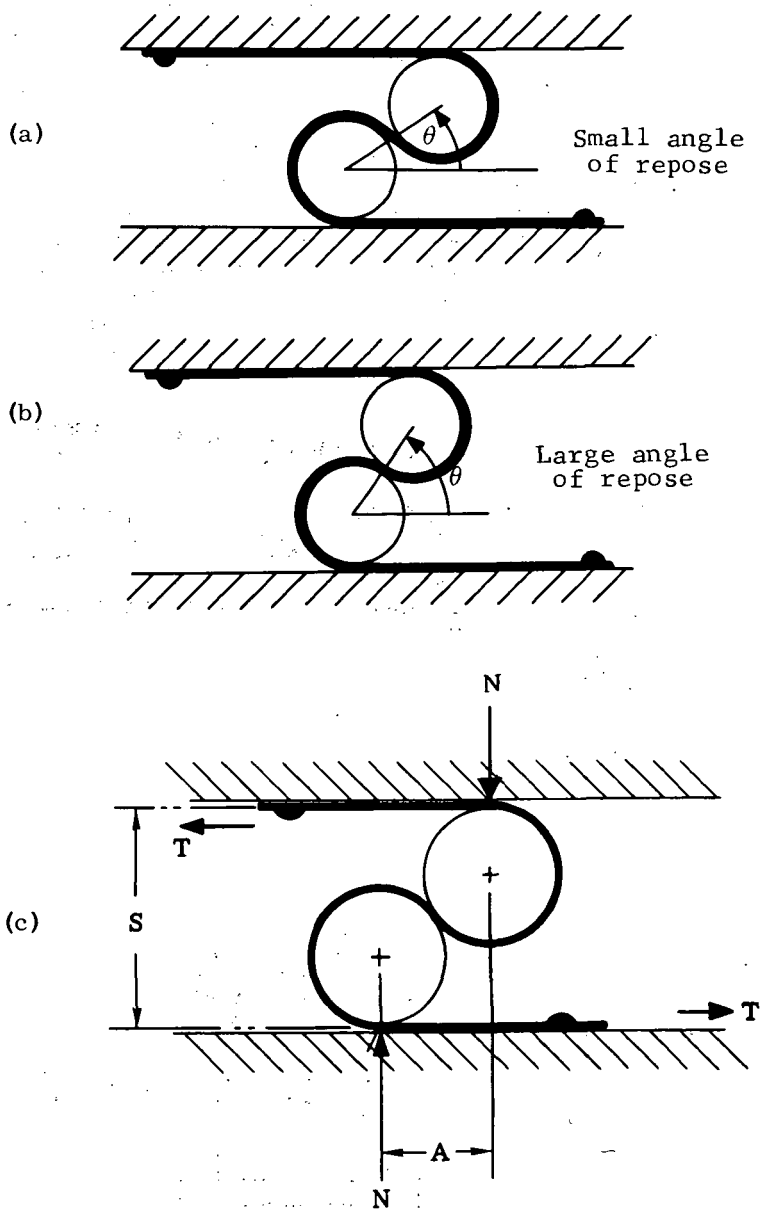


Figure 1. Basic Relations and Extremes of the Rolamite Geometry

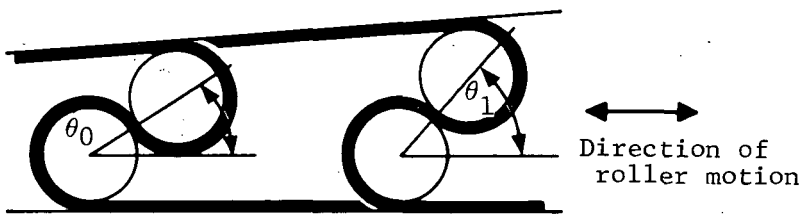
If T and S remain constant, and A is changed (so that the roller diameter changes from a value essentially that of the distance between the guide surfaces S to one-half S), the normal force changes from a lower value of T to an upper value of infinity. Of course, this affects the over-all frictional situation; it affects how much load it can support from the side; and it affects the ability of the cluster to roll over obstructions, machine marks, and contaminants in the system.

* * *

FORCE GENERATION WITH NONPARALLEL GUIDES

Percival pointed out that generation of forces results from nonparallelism of the guide surfaces, as in Figure 2 (a). "If you want to generate large forces along the axis of the rolamite, consider tapering the guides. Use a good stiff band and then lock up the system with high band tension. You will find that if you push the rollers to one end and then take your finger away, the rollers come back at a rapid rate. I used a large, rather stiff spring on the end of the band, to give some compliance. As I pushed the roller into the tighter section of the guide surface, the extra band needed for the larger wrap angle was obtained by stretching the spring. It did not take much motion of the spring to give quite a bit of motion in the roller."

(a)



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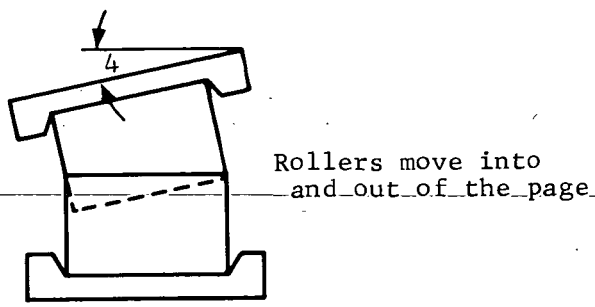

Figure 2. Two Types of Guide Parallelism

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

EFFECTS OF GUIDES NONPARALLEL TO THE AXIS

A second type of parallelism or nonparallelism was described by Bell--the guide parallelism along the roller major axis (Figure 2). In this case, band tension tends to rotate the rollers so that they are not properly aligned with respect to the direction of motion. There is a side component of motion which must be opposed if the rollers are to move in the desired direction. The opposing force comes from the rollers contacting the guide surfaces; the rollers slip on the guides and rub at the point where the rollers contact the guide surfaces, resulting in frictional losses. Some calculations indicate that the losses are proportional to α, the angle the top guide makes with the bottom guide, the band tension. The losses are also a strong function of the angle of repose.

* * *

COMPARISON OF TYPES OF NON-PARALLELISM

As Percival summarized it, "there definitely is a difference between the two types of parallelism discussed. One type does not show up as frictional losses but rather as force generation. On the other hand, the second type requires that the rollers move while skewed to each other--sliding has to occur both perpendicular to the axis of motion and on the guide rails. As to the magnitude of parallelism, the best that I can say is that we typically try to hold about 0.2 percent across the width, and about the same along the length. You might be able to live with force generation in one direction, but not a friction."

Nonparallelism of the first sort can be mitigated with spring-mounted bands.

* * *

GUIDE RAIL HEIGHT

Guide rails are necessary to absorb side loads. Also if there were no guides and the rolamite were operated on its side with a loose geometry, the rollers could fall away.

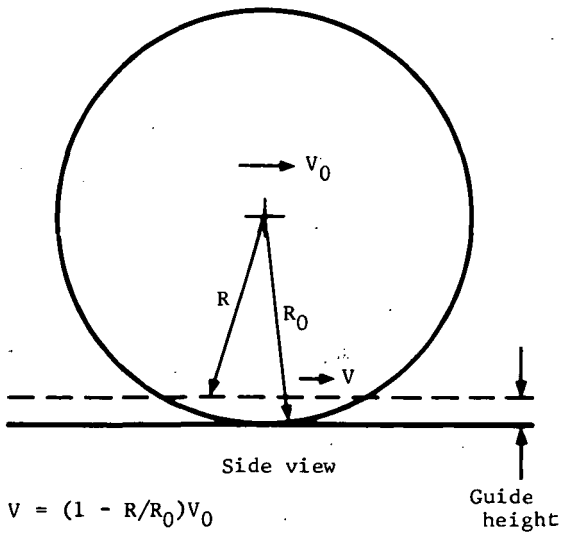

Figure 3. Relative Velocity at Point Where Guide Touches Roller

Dean Gladow illustrated the phenomena that are occurring on the rail. "Obviously, the center of the roller is moving along at the velocity of the roller cluster. On the other hand, the velocity of a point in contact with the guides has no forward velocity at all (Figure 3). Therefore, to keep the total friction at a very low value, use side rails only where there is very little velocity, so that there will be very little energy loss. This means that the height of the rail should be as small as possible compared to the roller diameter. Typical values I have seen used are about 1/30 of the roller diameter. As for the actual shape, I think it is pretty obvious that there can be some relative motion between the guides and rollers, so we try to come up with a shape that keeps the rollers toward the center."

* * *

GUIDE RAIL SHAPE

Lon Bell pointed out that the corner shape on the guide rail is a very important design consideration. "If the guides have a radius at the corner, and the band and roller contact the guide at this point, the band can experience stresses appreciably higher than the stresses associated with bending the band around the rollers. As a result, the band is likely to fail at this point. One technique we use to prevent stress concentrations at this point is to undercut the radius (Figure 4).

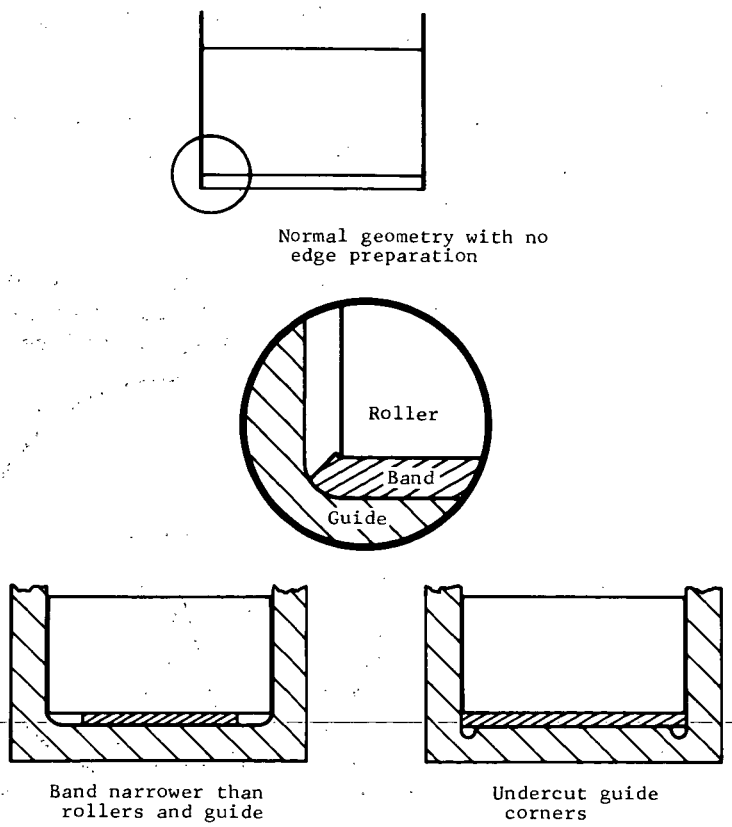

Figure 4. Methods of Eliminating Bending Stresses at the Edge of the Band

However, the undercut is hard to make on small, precise devices. A second solution is to make the band narrow compared to the guide width so that the band does not contact the roller at the corner. Finally, the band can be attached to the roller to prevent the band from coming in contact with the corner." J. M. Fowler pointed out that when the corner is perfectly square, any skewing will cause the rollers to gouge into the side rail and lock.

* * *

BAND WIDTH

In reply to a question of band width compared to roller length, Dean Gladow answered, "We have made bands wider a time or two, but only in very specialized applications. I would say that usually you make the band smaller than the roller. Of course, the interesting thing about Lon Bell's idea of not making the band as wide as the roller is that a guide radius equal to the band thickness can be accommodated. Naturally, the rollers can be contoured as well. However, when you do this, you get into secondary effects such as increased rubbing.

* * *

RTI HINGE APPLICATION

Replying to questions about RTI's application of rolamite as a door hinge, Dean Gladow discussed design. "The door had rollers 1/2 inch in diameter and the guides were 3/4 inch apart. Now, if the door opens a maximum of about 120 degrees, the rollers also rotate 120 degrees (Figure 5). The interesting thing to note is that the band was designed to wrap about 250 degrees around the rollers. But since the rollers only move 120 degrees, there are 150 degrees of wetted perimeter where the band never leaves the rollers. An obvious means, then, of keeping the rollers in position is to put a pin through the band onto the rollers.

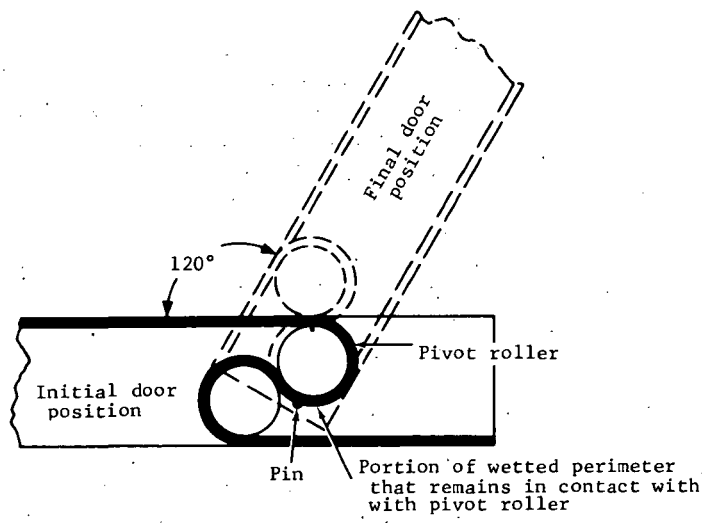

Figure 5. Door Geometry Showing Placement of Holding Pins

"The pin through the pivot roller and the band supports the door, and a second pin supports the auxiliary roller, so that things cannot slide up and down. If you can use it, pinning or spot-welding the band to rollers is a very convenient means of holding rolamite elements in place. Band tension could hold the rollers in place, with the proper tension. I think over a long lifetime you probably would find microslippage, although very little slippage would occur in one traverse.

"I am sure moment on the rolamite as a result of the dead weight of the door load affects the diameter of the pin. The door hinge was not a finished design, and I have not calculated stress loads on the band or the pin."

* * *

BAND TENSION ON PINNED ROLLERS

When a band is pinned to the roller, tension at each end of the band is not of equal magnitude. However, after a device of this design is operated a few times, the tensions equalize.

* * *

COEFFICIENT OF FRICTION VERSUS BAND TENSION

Robert Demers referred to Mark Percival's tests of coefficient of friction versus band tension for different thicknesses of bands. "I could not see much correlation between the curves, especially for the 1-mil-thick band which seemed to go in the opposite direction of the other thicknesses. Is there any reason for that?"

Percival replied, "I think the 1.5-mil-thick results differed by about 25 percent from the rest. The data presented were limited as far as friction data were concerned. Usually, results are taken over a period of months and then averaged. As mentioned earlier, sufficient time had not elapsed to redo the experiments to see how reasonable and consistent our data really are. I think the variations are acceptable as far as friction measurements are concerned. There was a factor of about 2 in the coefficient of friction from the lowest to the highest value. The variation you mention seemed to be independent of band thickness and of band tension, so I think it was just the scatter of the experiment itself. Intuitively I feel there is no reason why the coefficient of friction should be affected by either band tension or the thickness of the band itself, and this seemed to be borne out in the data presented."

* * *

FRICTION IN ROLAMITE GEOMETRY

The friction that does exist in the rolamite geometry seems to come from a combination of microwelding, elastic deformation of the roller on the surface, and hysteresis effects.

Chairman Bell noted that in contrast to rolling a cylinder down a plate, in rolamite the band acts as an intermediary, transfering stresses or loads from the guide surface to the roller. It does not have a point contact as in a cylinder rolling on a surface. In other words, the band touches the guide surface at a point where the roller does not touch the band.

Mark Percival added, "It was interesting that the coefficient of friction that I measured for the full rolamite device was less than the handbooks give for rolling one cylinder on one plate down an inclined plane, so I think the band is relieving some of the contact pressure you were talking about. You would think, offhand, that rolamite friction would be about four times as great, since there are four contact points, if you consider roller-to-band contacts. Yet the total coefficient of friction is less than for just one roller rolling down an inclined plane. The coefficient of friction is, I think, very much enhanced by remating of surfaces, or maybe we have a cantilevered portion of the band, as you mentioned. As Dick Cadman showed in his talk, the band tends to spread the contact pressure out between the roller and the surface, keeping the contact pressure at a very low value, and increasing the ability of the two materials to roll over each other without sticking or elastically deforming."

Tight geometry does not increase coefficient of friction as drastically as one would expect. For a 1/2-mil band and a 2-mil band, the "tightness" with regard to gap between the rollers is significantly different, yet the coefficient of friction seems to be about the same up to tensions of 6 pounds or so. Yet the roller spacing with the 1/2-mil band is within 1/10 of a thousandth of an inch or so of being a tight geometry.

* * *

HIGH ENERGY FORCE RELEASE

A Sandia device which generated sufficient force to shear rivets was described.

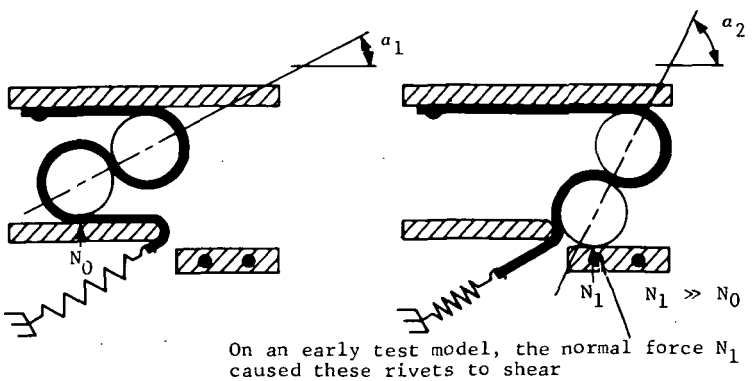

Figure 6. Expanded Channel Rolamite

The normal force is the product TS divided by A. If A is nearly zero where the channel expands, the rollers will generate large normal forces at this point. Expanding the channel can result in very high forces, enough to shear rivets as a result of the expansion.

THEORETICAL FORCE GENERATION MEASUREMENTS

A participant asked whether all variations from theoretical force were due to friction. Dean Gladow replied, "If you plot a complete cycle of motion of a rolamite using a load cell, you will find that the force curve generated looks like the one shown in Figure 7. On the reverse cycle, the curve still has the same shape, but it is displaced by an amount equal to twice the frictional loss in each direction. After hundreds of cycles, the curves are still distinguishable with the same general shape, although the peaks gradually decrease.

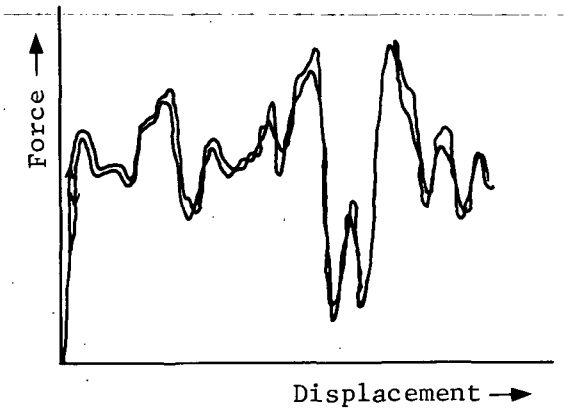

Figure 7. Typical Force Deflection Trace Made With Rolling Friction Test Apparatus

"Several things--machine marks on guide surfaces, localized variations in band thickness, and contaminants which have entered the system--combine to affect details of force generation. I think there is one thing of importance--after hundreds of cycles you are still able to recognize the force curve, but if you loosen the tension and move one roller just one degree, you will get a completely different force curve out of the system."

* * *

BAND SURFACE IMPERFECTION AND NOISE

Dick Cadman conjectured that the noise percentage of the total force ranges from 3 percent to about 10 percent with less carefully controlled tolerances. With good finishes on the guides, rollers, and the band itself, the variation is about 3 percent. The band is of great importance because band thickness is controlled only to about 5 percent accuracy for bands of about one thousandth of any inch in thickness. Since the force is proportional to the band thickness cubed, variations of 5 percent cubed become very important.

The manufacturer's 5-percent tolerance is the variation from nominal of a roll of material, and not necessarily the variations from point to point over a given band. Variations in a roll of material and for different rolls are very important if reproducible force-generating characteristics are sought from one band to the next. Variations of ±5 percent in thickness can

result in force variations of ±15 percent. Also, variations within a band are important for devices that must generate precise forces (or no force at all), since these anomalies add to the noise.

* * *

BAND STRESS FOR ROLAMITE OPERATION

Replying to a question about yield strengths for band operation, Chairman Bell cautioned the participants, "If very few operations are required of a device, and the band must not absorb significant energy from permanent deformation, the material should be stressed at or below the 0.02 percent offset strength. Unfortunately, only the 0.2 percent offset yield is generally tabulated. For most materials, this stress should be derated by about 10 percent as an operating limit. On the other hand, if you want single operation and the force generation capabilities of the band are not important, or if the band is quite thin for the roller size, then the stresses can be closer to the yield stress. For millions of cycles, the band must be stressed below its endurance stress.

"The stresses that can build up in severe environments must be kept in mind, especially for devices that operate millions of cycles. Generally, smooth roller cluster motion is assumed and stresses are calculated from statics. However, the rollers nearly always terminate their motion in one direction by hitting, dropping, scraping, or contacting some barrier that disturbs the geometry or puts localized stresses on the band. Also, if the band has cutouts, stress concentrations result. In either case, if you assume smooth motion and ignore the effects of cutout on stresses, the resultant stress calculations may be way off--often by at least a factor of 2."

* * *

TENSILE, BENDING, AND CONTACT STRESS

William Holliday was interested in accounting for a combination of bending, compressure, and tensile stresses in the band at the point of contact between the rollers or a roller and a guide surface. In his friction work Percival had calculated the combination of tensile stress due to band tension and bending stress. "I tried to work in tensions on the band that were below 50 percent of the yield stress, to get away from stress concentrations, plasticity, or any other side effect that would modify the band's behavior. I do not know if anybody has really considered contact stresses in the design of rolamites themselves for production. My interest was mainly in making sure that the experiment, as performed, was as close to an ideal geometry as possible. With regard to contact stresses at points of impact, I did notice in our tests, where the band and rollers fall 1/2 inch and impact on a solid stop, that after 40 or 50 actuations the band permanently deformed to such an extent that you could see the damage to the band."

STRESS LEVELS

Gladow's experience led him to comment that stresses become important in two situations: upon cluster impact and in geometrics where the angle of repose is very nearly 90 degrees. If neither of these situations exists, the stresses are typically very small, compared to the tensile stresses and flexural stresses in the band. For example, in normal bearings stresses range from 100,000 to 500,000 psi, while typical stresses in the normal rolamite are from 300 to 10,000 psi (with the angle of repose less than 75 degrees and no impact). Even the higher stress is only 3 percent of the yield strength of most band materials.

* * *

BAND MATERIALS

The primary disadvantage in using soft materials, such as plastics, for bands, is that they creep or set after a given time. Then, if the cluster is moved, it tends to return to its original position. Secondly, forces generated by band cutouts or preform are not as high as with metals. Plastics are very valuable in mock ups or prototype models, but probably finished devices will be using metal bands.

Some very high-strength aluminum alloys become interesting for applications where force generation is not important. Bell pointed out that the governing parameter in this case is the ratio of the yield stress or endurance stress divided by Young's modulus. Since, for aluminum and some magnesium alloys, Young's modulus is very low, this ratio can be quite high. This ratio, called the flexivity, determines how thick a band can be wrapped around a roller of a given diameter.

* * *

LOW FRICTION DEMONSTRATION

In a discussion of energy losses in rolamite as qualitatively observed by several participants, Norwood described a Sandia device. "When a large model with 3- or 4-inch roller diameter, two hollow aluminum rollers, and a 5-mil uniform Mylar band was placed on a level table, the rollers would roll in a given direction. If you turned it around, the rollers would stay at that end, which gave you the feeling that the table was flat and not affecting their motion. And yet, when the whole device was turned over, they rolled back. What was happening was that when the band was at the top (Figure 8), it was at a higher potential energy state than when it was on the bottom. The potential energy difference due to the change in band elevation (or the band weight) was enough to make the rollers roll.

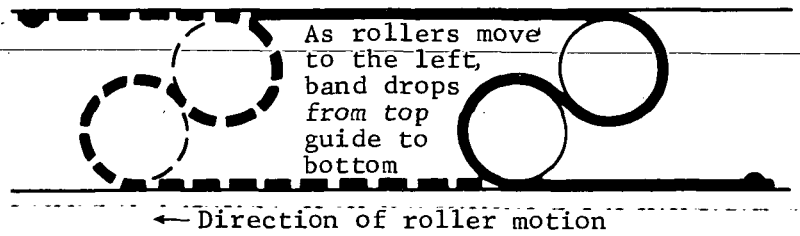

Figure 8. Effect of Band Weight on Roller Position

SYMPOSIUM REVIEW

SESSION III-C

SYMPOSIUM REVIEW

INTRODUCTION

A review session for the Symposium on Rolamite allowed general participant discussion of topics isolated by the separate workshop sessions, as well as final questions and evaluations. Mario DiGiovanni (Statham Instruments) and Charles R. Hughes (Hughes Engineering) presented specific applications of rolamite designs; R. W. Diller (Technar, Incorporated) summarized some promising multiple-function aspects of rolamite switches; and Fred Duimstra (Sandia Laboratories) discussed rolamite damping techniques. Paul Hanson chaired the session, and began with comments directed to the unique opportunities which rolamite design offers American industry.

APPLICATION OF ROLAMITE IN INDUSTRY

Paul Hanson (RTI)

I would like to speak for a moment on the practical application of rolamite in industry. Each of us is here today basically to find a way in which we can capitalize on this technology. Our thanks are owing to Sandia Laboratories and to the Atomic Energy Commission for their willingness to unveil this technology and make available to American industry something of this magnitude. I would like to comment on two points.

First, it was quite apparent after rolamite had been invented at Sandia Laboratories, that the concept offered not only a unique technological capability but also a unique economic capability. Rarely do we get a new technology which will improve a product and at the same time reduce cost. Usually what happens is that we get a new technology which improves a product but increases the cost.

Sandia and the Atomic Energy Commission unveiled the technology and made it available to American industry for a number of reasons. I think it is apparent what might happen to American industry in world markets if Japan, Germany, and other highly mechanically and engineering oriented countries were able to get a significant grasp of this technology and, with their rapid turnaround time, begin to capitalize on it domestically and abroad.

The second item is the general patent situation. There is both an advantage and a disadvantage to having a technology available to everyone on a royalty-free license basis. The advantage is that the details of the technology are available to everyone and not kept under wraps through patents and trade secret material. The disadvantage is that often companies are not willing to go into an area which they feel competition may be entering at the same time, and thus risk a proprietary position.

The breadth of rolamite applications provides a unique advantage to American industry, whether or not it may be apparent to everyone. To explain, let's compare the rolamite with the transistor. The transistor as a technological entity can perform three separate but not mutually exclusive functions. For the rolamite, Sandia has been able to list a total of 257 separate but not mutually exclusive functions.

What does this mean from the viewpoint of economic opportunity for United States industry? Simply this: the spectrum of the technology is so broad that it allows United States industry to go forward to exploit the technology and still feel reasonably certain of obtaining a proprietary position. United States industry should not worry about the fact that there are royalty-free licenses available to everyone. With this type of arrangement a company can develop a particular application

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utilizing rolamite, patent it, and receive full proprietary protection. The only thing a company does not have to do is pay a royalty to the Atomic Energy Commission for the privilege of using the technology.

HYBRID ROLAMITE PUMP

Mario DiGiovanni (Y. P. Engineering, Statham Instruments)

As manufacturers of strain-gage transducers and accelerometers we have had much experience in flexural suspensions. In this morning's session I made the remark to my colleague, Jack Chambers, that if Don Wilkes had consulted with us on his problems on the flexural suspension of his velocity meter, the rolamite principle might never have been invented!

I am surprised that our application of the rolamite principle is considered unique. We are using it in an energy conversion system where rotation has to be changed into translation. The problem is to pump fluid at the rapid rate of 160 strokes per minute against a pressure head of 200 millimeters of mercury.

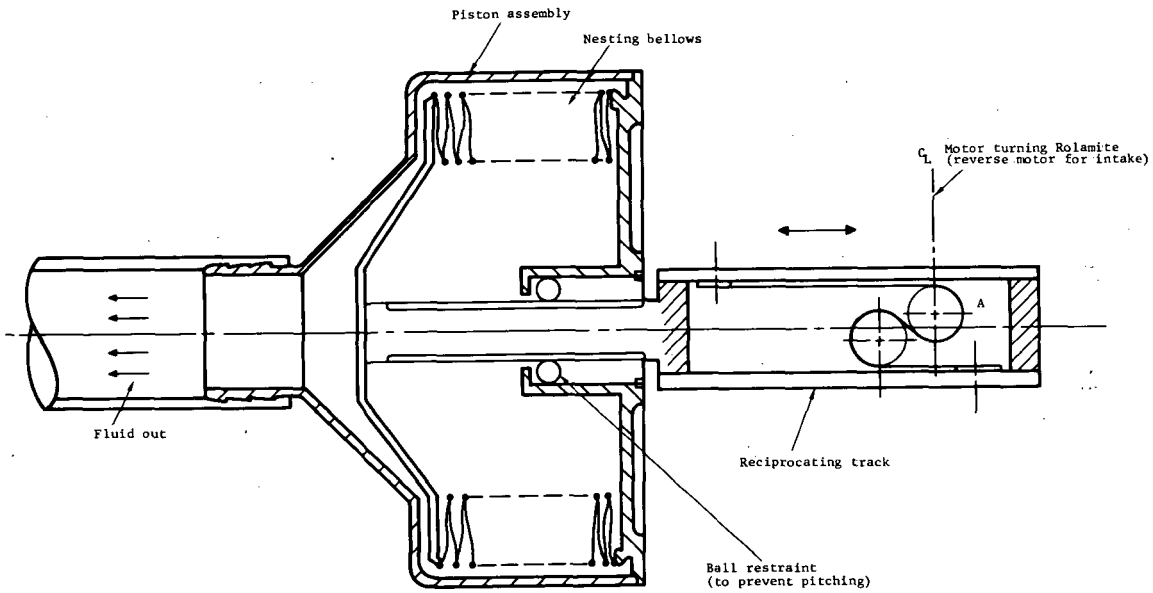

Figure 1. Statham Hybrid Rolamite Pump

The fluid is contained in a closed system and no fluid losses can be tolerated throughout the 1-inch stroke. With reference to Figure 1, the piston assembly consists of a 3-inch OD bellows of the nesting ripple type wetted on the outside by a low viscosity liquid. It is important that the system be as efficient as possible, have low inertial forces and a long life of approximately 10 years. The driving roller, A, of the rolamite mechanism is attached directly to a small DC torque motor. The rolamite mechanism is contained within a track which is directly attached to the bellows piston. Pitching of track is prevented by balls rolling in a dry film lubricated channel. Return stroke is accomplished by reversing polarity of the DC motor. To date we have had gratifying success with this hybrid rolamite pump. Our concern is band fatigue, as our rollers are less than 3/8-inch in diameter; however, I'm certain we can solve this problem by a redesign, if necessary, in the rolamite geometry.

THE MULTI-PI GAGE

Charles R. Hughes (Hughes Engineering Company)

Our application employs a different configuration in guideways than those previously discussed. Instead of parallel guides, we use a circular channel for guideways, trepanned into the inner face of a knob which houses the rolamite cluster.

Our device does not require a full rotation of the knob; therefore, a portion of the guideway can be used for clamping. The clamp, which is a fixed block interposed within the channel, clamps the band between itself and the inner surface of the guideway at one end of the band. At its opposite end is a projecting portion to which the eye of a coil expansion spring is attached. The other end of the spring is fastened into an eyelet in the end of the band, thereby maintaining a predetermined tension on the rolamite cluster to hold its geometry.

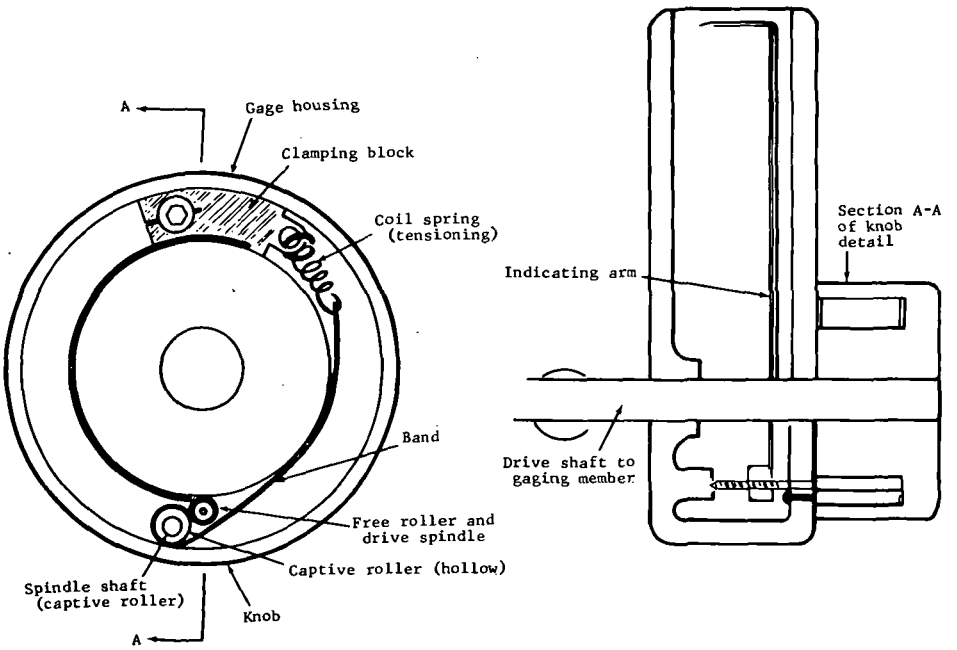

Figure 1. Thread Gage Device Using Rolamite

By making one of the rollers in the cluster captive, while allowing it to revolve freely around a fixed shaft projecting from the mating part, against which the circular knob operates, the band will, through the action of the coil spring at its other end, force the cluster to keep its position in the main body of the gage. The knob, revolving around its central axis, carries the band through the rollers. This turns the rollers in a precalculated ratio controlled by the diameter of the inner guideway. Attached to its outer end, the free roller carries the indicating arm which shows the final readout by swinging through a 2-1/2-inch radius arc as the roller revolves the small amount allowable. By threading the outer end of this roller with a loose-fit thread, by which the arm is attached, we were permitted overtravel in one direction. This was absolutely necessary because of the limited amount of range in the gaging area, while sufficient rotation was needed to allow collapse for entry into the thread to be checked.

In our application, where only a small portion of the circular guideway is used, we can achieve magnification of the infinitesimal movement of the knob as it rotates the gaging means. Our instrument utilizes the principle that a given-diameter enlargement is always accompanied by a circumferential enlargement of 3.1416 times as much. Our gage head is basically a coil spring, which is made of the best wire size, as shown on all "three-wire thread measurement" charts, for the

internal thread we want to measure. The spring section is wound to conform to the same pitch as the thread itself. Using a multiple number of coils, the tool operates by forcibly unwinding this spring of predetermined configuration into the thread form of the workpiece being tested. The coils of the spring conform to the pitch diameter of the thread, and come to a firm stop after reaching this point. This is, then, the actual metal-to-metal contact size of the entire thread, and not simply a measurement of the mouth of the thread as in conventional plug gages.

We have named our tool the "Multi-Pi Gage." One ten-thousandth of an inch change of diameter is over three-tenths of a thousandth in circumference for one coil. This, multiplied by, say, six coils becomes a little over eighteen thousandths of an inch. This rotating movement, when extended to the radius of the inner surface of the guideway, which is three quarters of an inch, and then fed into the extreme guide-to-roller ratio, and thence to the indicating arm itself, which swings an arc of two and one-half inches radius from the center of the rolamite roller, produces a fantastic amplification of the original one ten-thousandth inch variation.

Rolamite was attractive to us not only because of its unlimited ratio possibilities, nonslip characteristic between band and rollers, and elimination of free play or backlash, but also because of the savings on additional hardware items such as special gears. We found that the rolamite concept functioned well in all aspects of its use.

ELECTRICAL SWITCHING WITH ROLAMITE

R. W. Diller (Technar, Incorporated)

In both the electrical switching workshop and electromechanical devices workshop we got involved in talking about things that are relevant to switches. This is a synopsis of the highlights of both. One of the things we began talking about with respect to switches in particular was, What do you expect from a rolamite switch? Suppose you are interested, as several people were, in producing a small snap switch: a switch by itself and nothing else. We presented some arguments, primarily economic, that tended to discourage this use of rolamite. Nevertheless, we have been aware of a general theme throughout the entire conference: we are interested in rolamite's extraordinary ability to perform many functions simultaneously. Rather than consider specific ways of making a switch alone, we hope that people will consider switching as another function to be performed by a multifunction device.

We also talked about specific things that are important to switching itself. Given, that one has decided to have some device that requires switching, what should be the method for arranging contacts? The first question or two came up about using the band for electrical contact. We discussed the fact that for low currents, for a limited number of cycles, this would be satisfactory; however, if one is going to be switching high currents of the order of amperes, or for many cycles, a number of things make band contacting very undesirable. One such thing occurring during many cycles of operation is that just bumping the band against the stationary contact potentially reduces the fatigue life of the band. An electrical consideration when dealing with larger currents is that arcing may, in time, actually take out pieces of the band, destroying it completely. At least there would be some substantial resistance heating unless one chooses some rather special, highly conductive band materials which may not be appropriate in your particular device. This heating will raise the temperature of the band to the extent that fatigue properties may very well be degraded. We also talked about putting a contact on the band, but no one really came up with a foolproof scheme of attachment. Spot welding or soldering really destroys the fatigue characteristics of the band. So there was no accepted way of actually making contact with the band.

It seemed quite reasonable to suggest the rollers as a place for the contacts. Several advantages are evident. Because there is a lot of material in the rollers, when working at high currents you can afford to let it wear away. Furthermore, because of the large mass, it is not going to get too hot. It is possible to plate the rollers, and it is possible to laminate them with varying insulators or conductors. What then should the rollers mate against, and where is the

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other contact? That can be in a variety of places. One particularly promising place is in the guide surface of the channel. It is relatively inexpensive to fabricate a printed circuit that you can actually use as a structural part of the case.

We also talked a little about actuation, which brought us back to the original position: that we do not want to build a simple switch alone. A reason is that we may very well be interested in sealing the device. If you seal it somehow, you have a terrible time trying to get into it with the actuator. This is not to say it cannot be done. But if, for example, you want to put a push rod or a pulling tongue in the device, you have to go to some kind of seal, which causes friction you originally wanted to eliminate through the use of rolamite. Thus there are ways of getting into rolamite devices, and in some cases they might be quite satisfactory.

To get away from the actuation problem, a more sophisticated switch would turn itself on and off. So we get back to the premise of using a rolamite device to do something else--sense environment, for example, and not be actuated from the outside. So, rather than design a switch by itself, we come to a central theme of the conference: it is important to use rolamite to make use of its ability to perform multiple functions in the same device.

ROLAMITE DAMPING TECHNIQUES

Fred Duimstra (Sandia Laboratories)

There was considerable interest this morning in one of the workshops on the methods that we have used to provide damping in rolamite devices. To review it, I will speak of the type of components we are presently working on at Sandia.

* * *

FLOW PAST ROLLERS

In the accelerometer or g switch type of application, we use the rollers themselves as a sensing mass so that any external g field will exert a force on the rollers to cause the rollers to move from one end to another. One of the ways we can accomplish damping of this roller motion is by filling the device with a fluid and pumping the fluid from one side of the rollers to the other. If we use a silicone fluid, which for a number of reasons is one of the better damping fluids we have found, and if we simply pump the fluid past the sides of the rollers, we will find that we get variable damping effects over a military temperature range of $\sim$ -65°F to +160°F. This is largely caused by the variance of viscosity of silicone fluid over this temperature range. The fluid flow equations which apply indicate that if the flow is laminar then flow rate will depend on differential fluid pressure and fluid viscosity. The fluid going past the side of the rollers goes through a long flow path and the result is a more or less laminar flow along the sides.

We have no actual data to support this as yet, but we are hoping that, in some future devices, we might be able to actually do away with the guide rails in the corners of cases and perform a certain amount of flotation of the rollers from the side walls by pumping the gases or fluids past the side and actually provide some roller support (see Figure 1). This might make it easier for us to form cases, since a little less precision would be required.

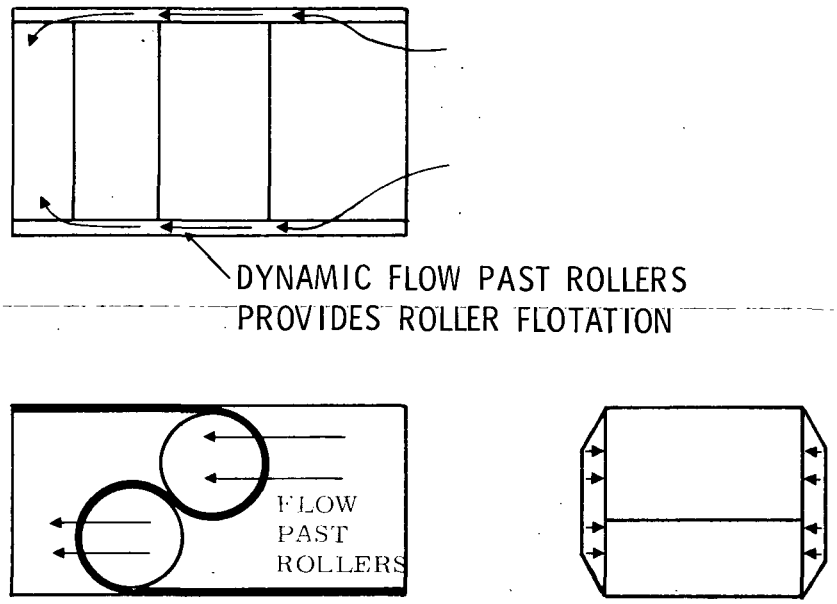

Figure 1. Fluid Damping

* * *

METERING

If we go to a fluid metering method whereby we can change the laminar flow to turbulent flow, we find we can make the fluid flow more or less temperature compensate for itself so that the changes in viscosity of the fluid now have little effect on damping effect. We get something that works better over the temperature range. I will illustrate a couple of ways we have found to intentionally produce turbulent flow.

* * *

BAND ORIFICING

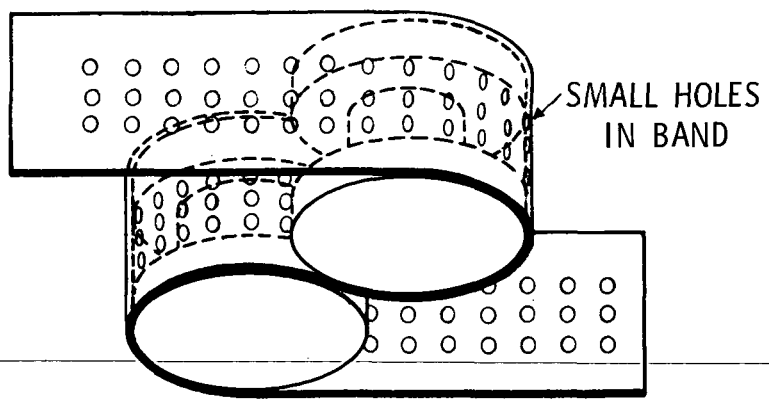

Figure 2. Band Orificing

Put a groove in the roller, and put a multiplicity of holes down the center of the band. No matter where the band is sitting, we can run fluid through these holes. Since this is a thin band, the small holes produce a sort of sharp-edged orifice effect which will help maintain turbulence (see Figure 2).

* * *

SINGLE ORIFICE

Another method we are working with is to simply form the case with a groove down the bottom as in Figure 3, and pump the oil through a single, sharp-edged orifice in the band. There are certainly many other methods of performing this type of damping.

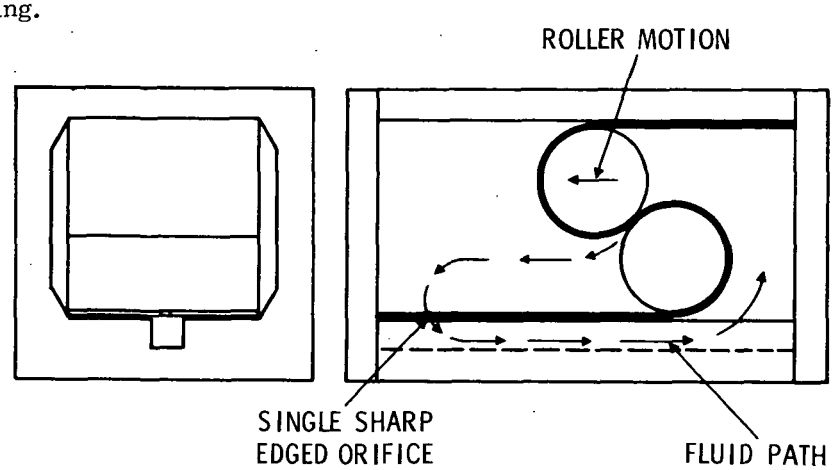

Figure 3. Single Orifice

* * *

AIR DAMPING

Of course, air damping is possible, but the problem we have had to date is that air doesn't have as much viscosity as the incompressible fluids. One therefore has to work with extremely small clearances to make it do a proper amount of damping. The small clearances require close dimensional tolerancing.

* * *

VERGE

One of the other ways that we can damp is by adding peripheral devices to the rolamite. One of the things we have built at Sandia is a rolamite verge. (Please see Electromechanical Workshop Session III-A-3 discussion for description of this device.)

* * *

VELCRO

In one of the work sessions, somebody suggested that Velcro might make a type of inertial damping material. That is something I intend to investigate a little further. Velcro is a nylon hook and loop arrangement, that requires a certain amount of constant force to peel apart. Of course nylon, being a plastic, exhibits a large variance in mechanical strength over the temperature range of interest. It turns out, if my information is correct, that on the Apollo spacecraft they used Velcro to keep various instruments and tools from floating around in the spacecraft. After the Apollo fire they changed all this nylon (which turned out to be highly combustible in a 100 percent oxygen atmosphere) to a steel material now made by Velcro.

STEEL "VELCRO"

If we can get a steel material with the proper characteristics (that is, the force required to pull the two materials apart is consistent over the temperature range, and the force required to pull the materials apart is some linear function of the applied force) we would have a useful device. If a rolamite had, for example, guide surfaces of the woolly part and a band out of the hook part, we should be able to get consistent damping. That is something I intend to try at the first opportunity.

SUMMARY OF QUESTIONNAIRE RESPONSES

A 55 percent return was received on a questionnaire which was sent out a couple of months after the meeting. The comments that were added to the Rolamite Symposium questionnaire might be of some interest to the readers of these proceedings. Most of those who responded to the questionnaire would have preferred more specific information regarding practical applications and trouble shooting. Only one man seemed concerned about proprietary considerations: "It is asking too much to expect a private company involved in research to expose the direction and results of his efforts to a general group which could contain competition."

Practical considerations are further shown by the fact that, while 17 respondents liked the interchange workshops, 26 would have preferred clinical workshops. Other suggestions included a combination of interchange and clinical workshops and informal discussion groups.

Only 8 of the 50 respondents had not requested information on rolamite before the symposium. So, on the whole, the following criticisms come from a relatively well-prepared group.

Some of the specific purposes and possible uses for rolamite thought of in advance by the respondents were:

Applying rolamite principle to a low load speed, unlubricated rotary bearing

Linear bearing and low energy contact

Carriage rollers

Possibility of low-force, low-current multipole switch

Implantable heart engine

Thermostat

Encoder drive--linear to rotary motion

Bearings operating in soil

Vacuum bearing

Switches

Pumping devices

Shock absorbing machine elements

Odometer as flywheel integrator type mechanism

Specific replacement for complex spring mechanism

Balances for window sash

Controlled torque mechanisms

Packaging

Pump changing rotary motion to reciprocating

There was quite a bit of repetition among some of these, especially thermostats and switching devices.

Comments on Session I (e. g., subjects which were treated too lightly or too deeply; other topics which would have been useful):

I would like to have seen more useful and/or practical applications of rolamite.

More time should have been spent on useful functions.

Go into great detail on applications and search for as many new ones as possible.

Speakers were unable to answer questions regarding practical applications. They were too wrapped up in the theory.

Areas of application were limited to a few examples which were repeated over and over again.

Stronger emphasis on applications and system integration would have been helpful.

Everyone seemed to be groping for practical applications.

For critically short time, review of general and specific applications (this was done pretty well) seems more practicable. Then, if time, individual problems could be sought out. Also, scheduling of such could be done in evenings or outside of designated conference time.

Some of the foreseeable problems associated with use of rolamite, such as tolerance problems and mass production.

Bands are the big problem.

The talk on dynamic forces was unclear. I could not take enough notes to understand it when I got home.

Some slides and displays were not adequate for the size of the crowd.

There was considerable risk in inviting participants' individual problems, as such could be far enough off the beaten path to not be appreciated by the majority.

Most of us needed a familiarization with the capacity of rolamite. The people who spoke had been living with it for over a year and were far beyond elementary concepts. Unfortunately, not all of us were that advanced.

I felt more emphasis should have been placed on the counterbalanced rolamite brought out by Wilkes and Gladow. It was mentioned in their example, but not mentioned again. This could be a useful concept.

A word or two should have been used to show how low in cost a rolamite could be made to offset the superprecision high cost devices developed for the Sandia thing. Had I not developed my own cost ideas about rolamite, I probably would have gone home disappointed because of cost, manufacturing, and inspection requirements.

Mr. Ford's opening speech was excellent. We have since used his slides to present a condensation to a number of engineers and technicians who were unable to attend, but were interested. Other presentations were judged to be high quality, authoritative.

As an initial technical conference, I believe the content was very much to the point. At a later meeting with more developed experience, it would have been disappointing.

I believe the first session accomplished its aim. It got the subject out in the open. Perhaps a second session, in a year or two, would be in order. Such a session could be directed more toward the hard core problems that industry has by that time encountered. In a year or two a lot of people will have tried to use rolamite and will have run head on into many problems. This will then help to sift the whole subject down to real practical applications.

Were the workshop leaders adequately prepared in the sessions you attended?

Some were prepared and able to help, others were not.

My impression is that workshop leaders were more concerned about trying to obtain information.

Workshops tended to dwell upon petty details or upon one man's problem. A good workshop leader will keep the subjects broad and variable.

Discussions were not controlled to subject matter as titles indicated.

They had some unresolved disagreements among themselves.

Were there additional topics you would like to have had covered in a workshop?

Perhaps an application brainstorming session.

I feel that specific problems of individuals in rolamite applications should have been dealt with.

Practical manufacturing problems, cost, and limitations.

Would like to have been able to learn more about the environmental capabilities.

Applying rolamite to a problem and discussing problems that would be involved in design.

How to achieve and maintain flatness in the bands when dealing with high volume applications.

Would like to have discussed some limitations that were not recognized in any of the talks or discussions.

Heavy load capabilities.

Application sessions run by other than fledgling company looking for clients.

Actual application to heavy loads encountered in industrial applications and the economics of practical applications.

There was considerable repetition of the need for practical applications and specific problems.

The only Yes-No answers that show dissatisfaction were to the question "Were you able to attend all the workshops you would have liked?" 19 said yes and 32 no.

END OF SUMMARY

We are continuing to search for the best combination of methods and processes to optimize transfer of technical innovations to the public. If you have comments in retrospect, please address

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